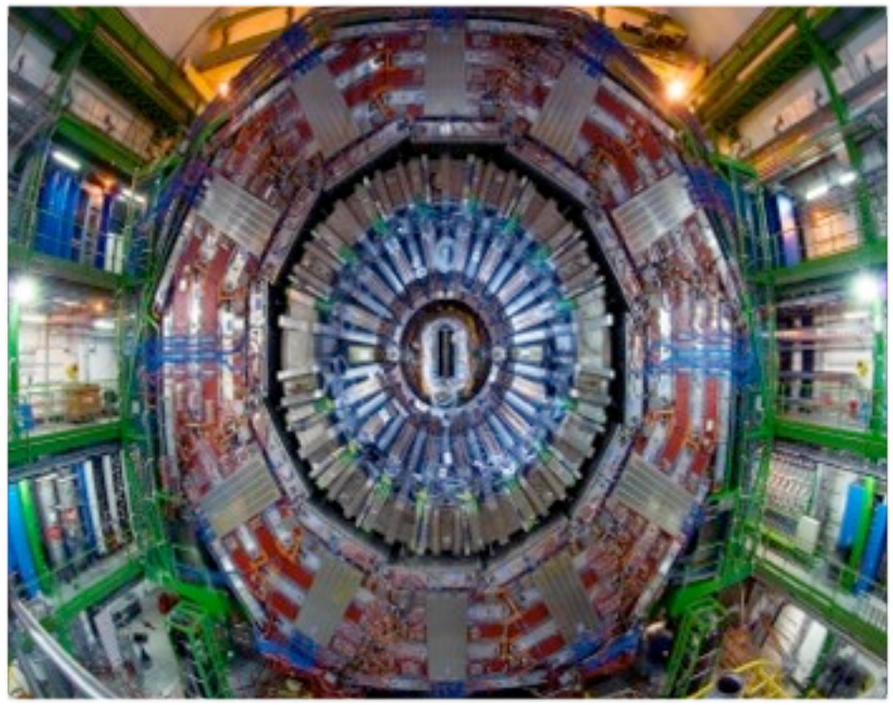
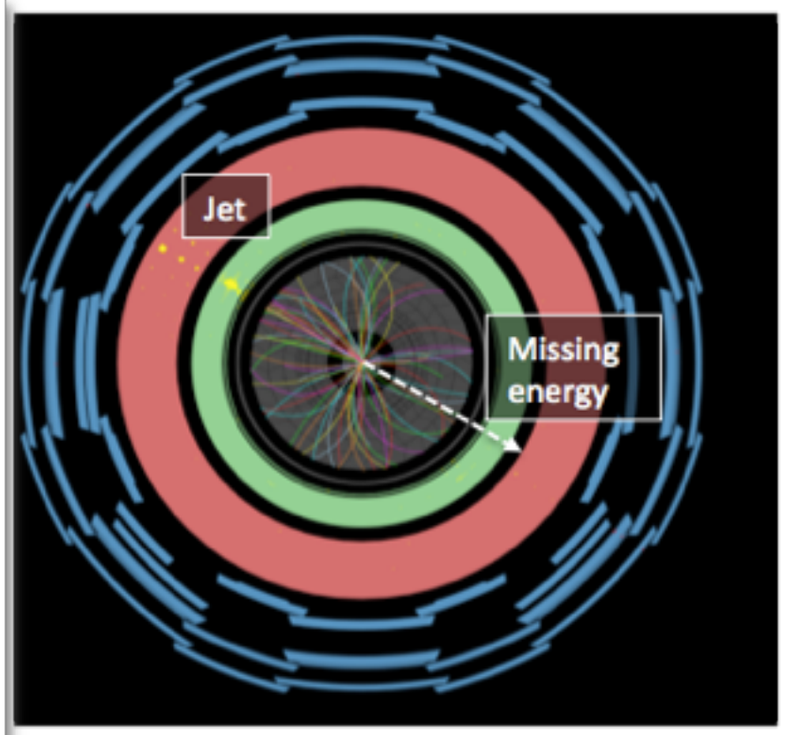


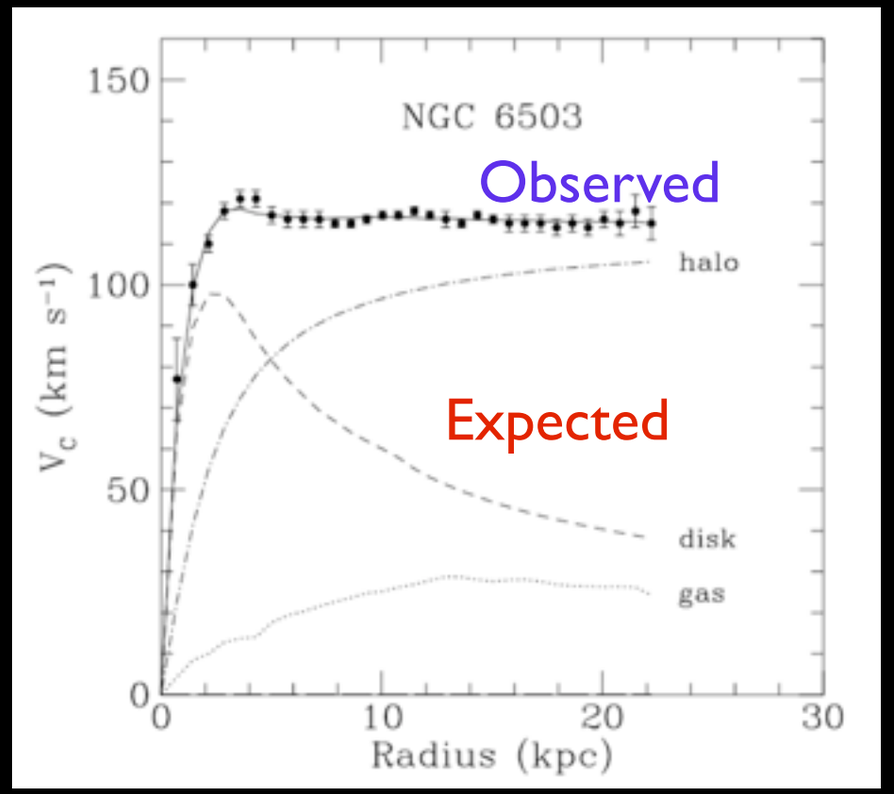


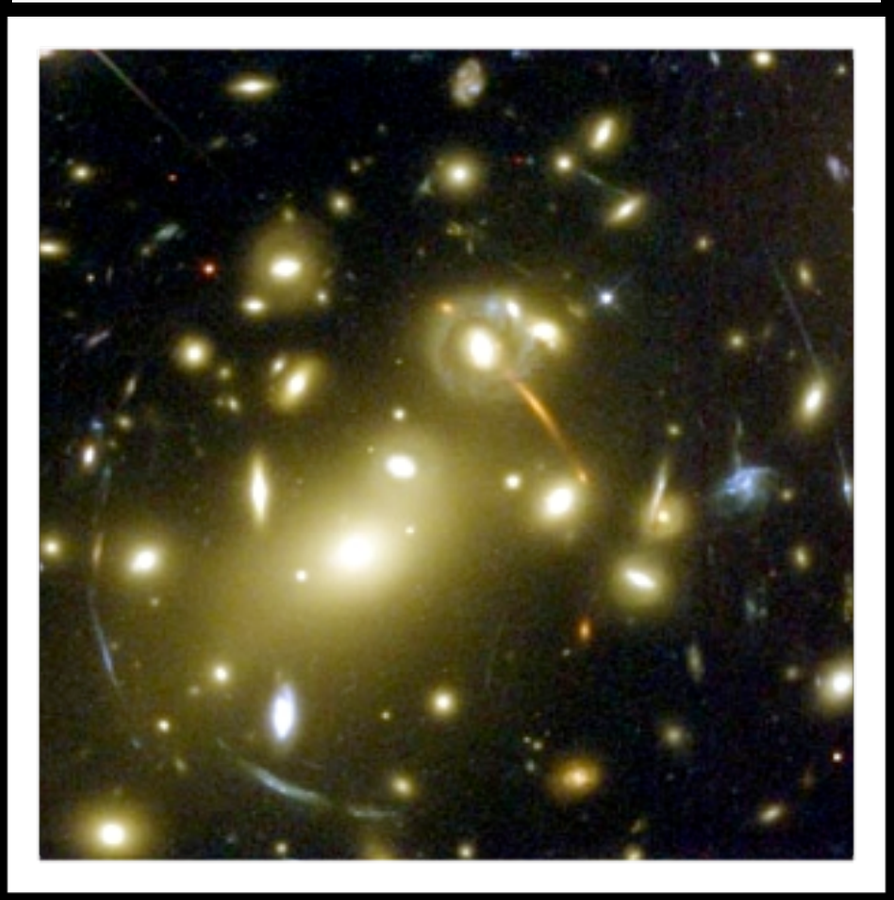
Dark matter searches at colliders

Sarah Alam Malik
The Rockefeller University

Evidence for dark matter

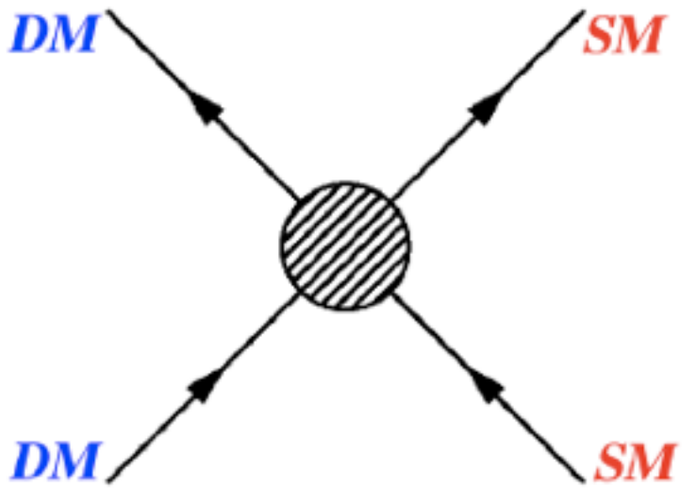
- galaxy rotation curves
- bullet clusters
- gravitational lensing





Searching for dark matter

- Dark matter (DM) is made of stable particle
- Weakly interacting with SM particles (WIMPs)
- Mass around the weak scale
- DM is entirely due to a single particle
- $\chi + \chi \rightarrow SM + SM$ is the only process important for determination of relic abundance



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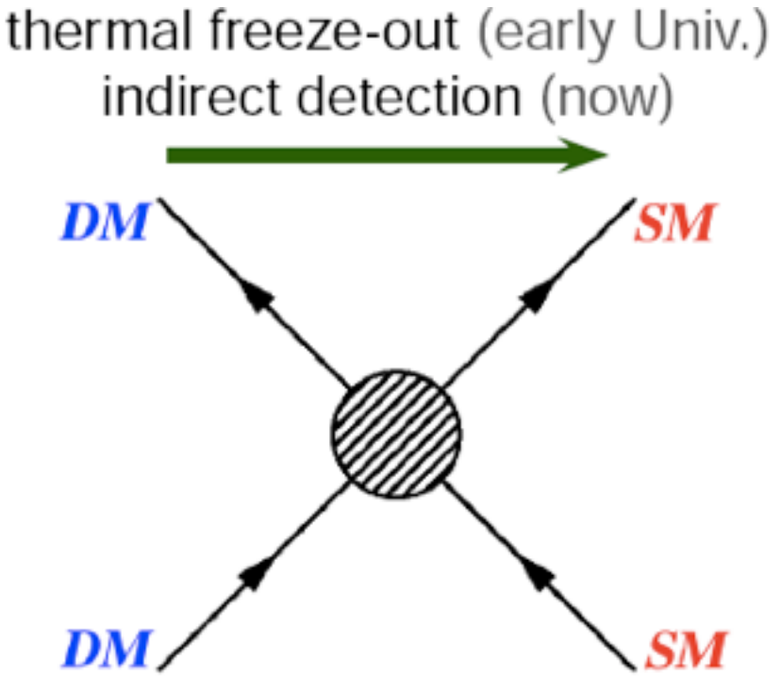
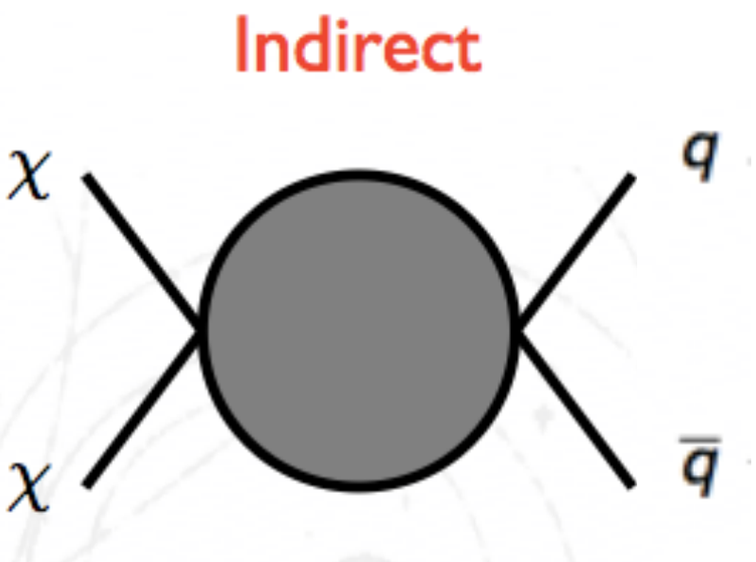


All three approaches probing the same interaction



Jim Buckley's talk

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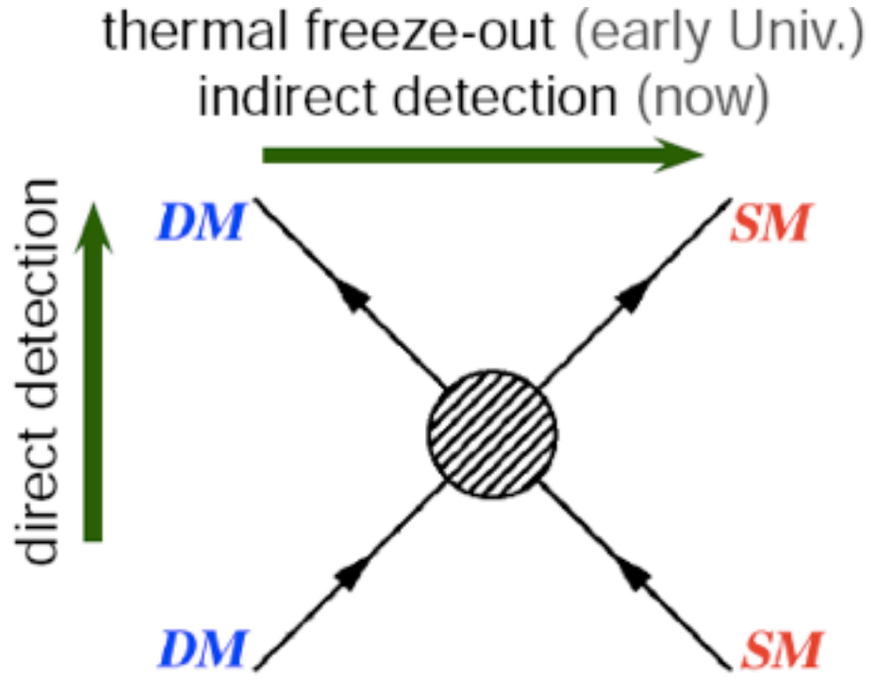

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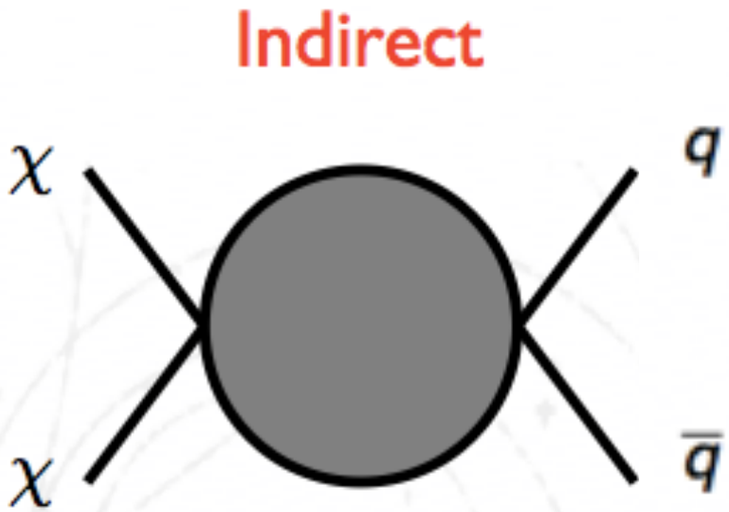

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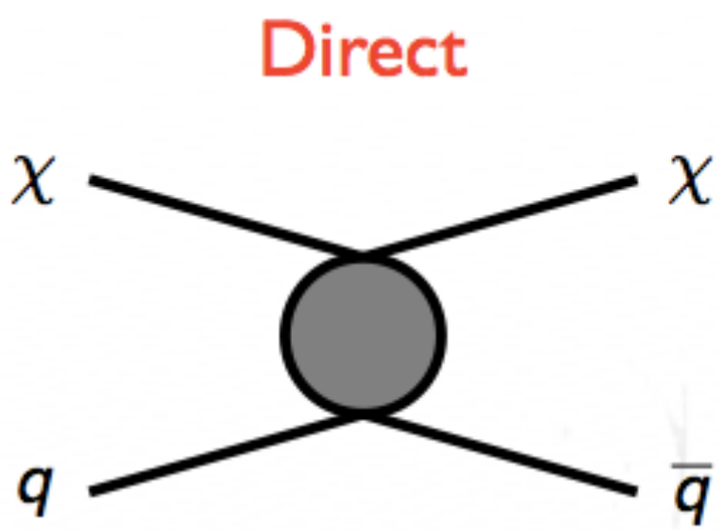

Jeter Hall's talk

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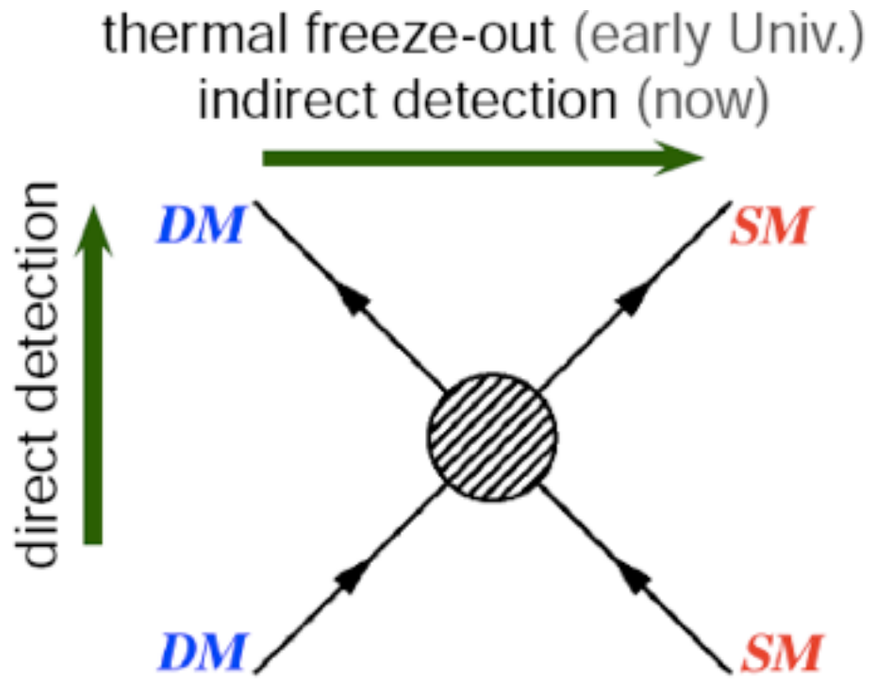

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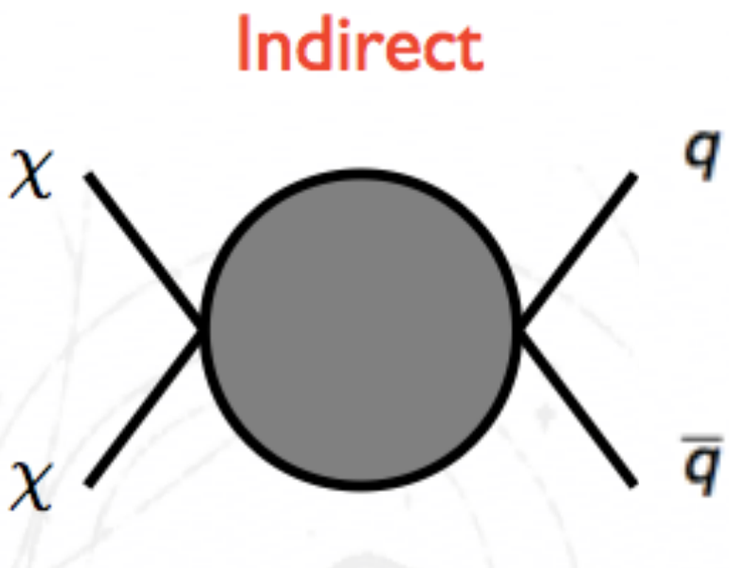
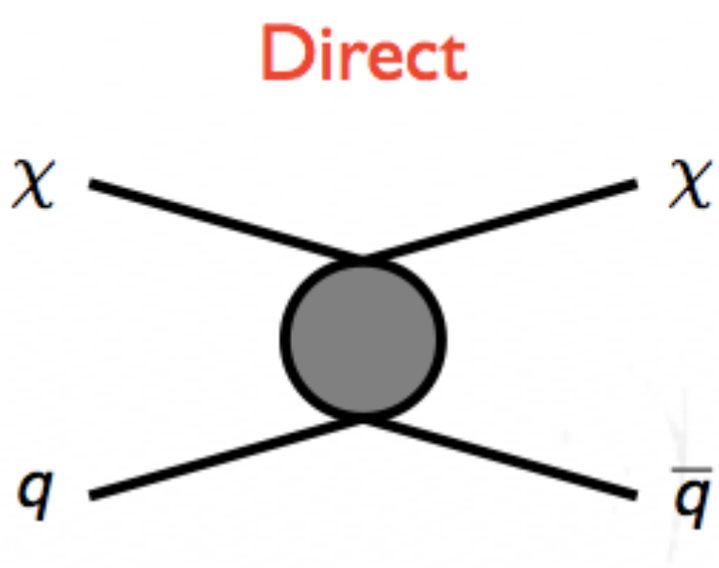


Jim Buckley's talk



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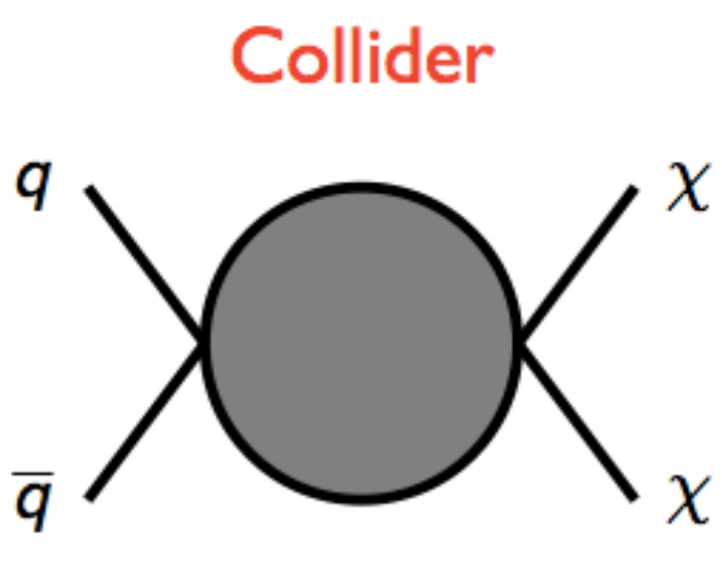

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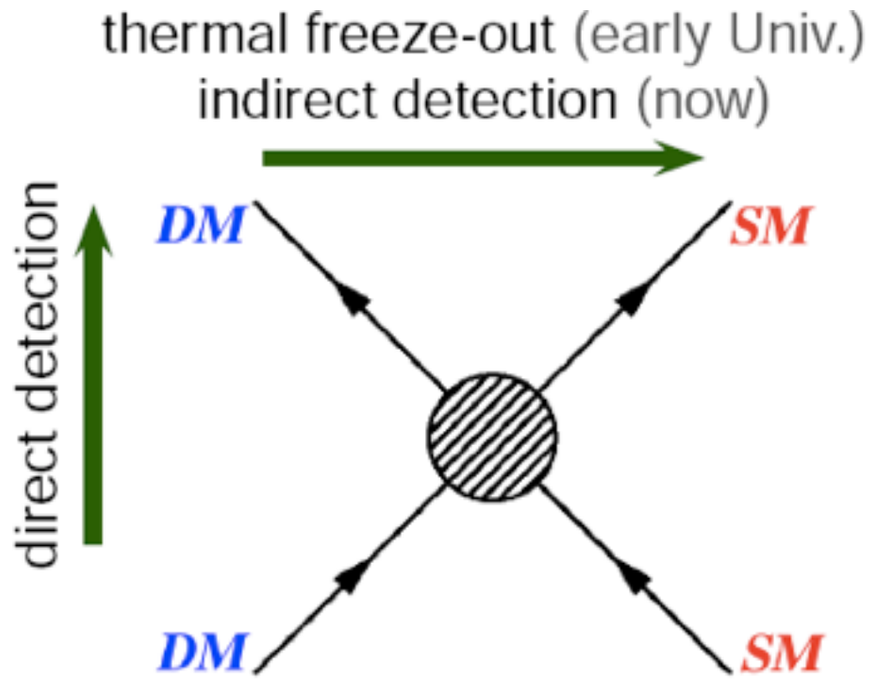

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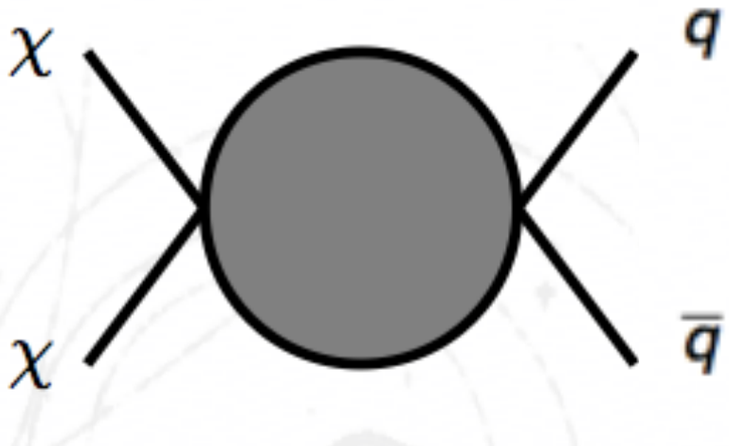

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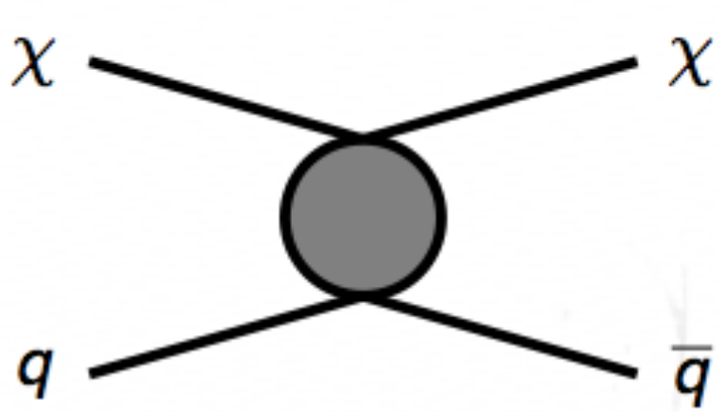

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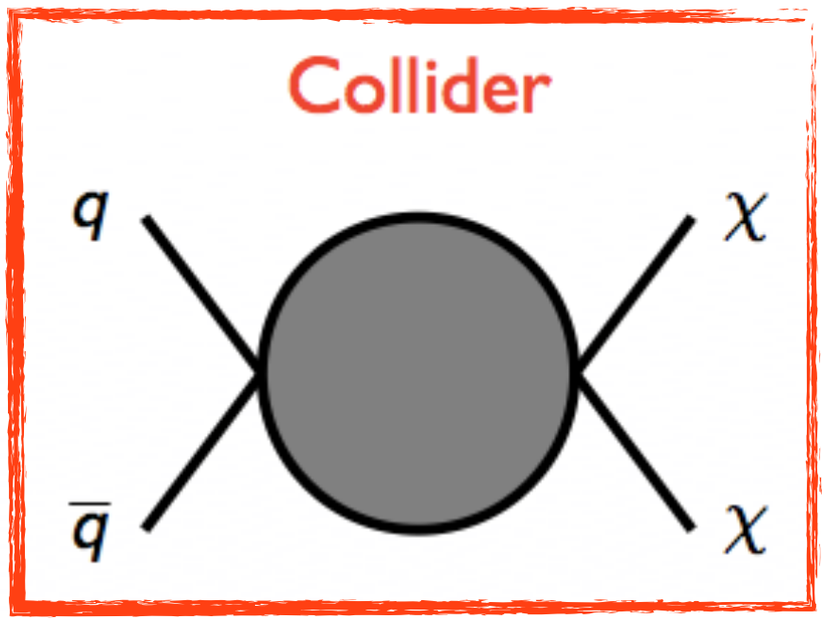
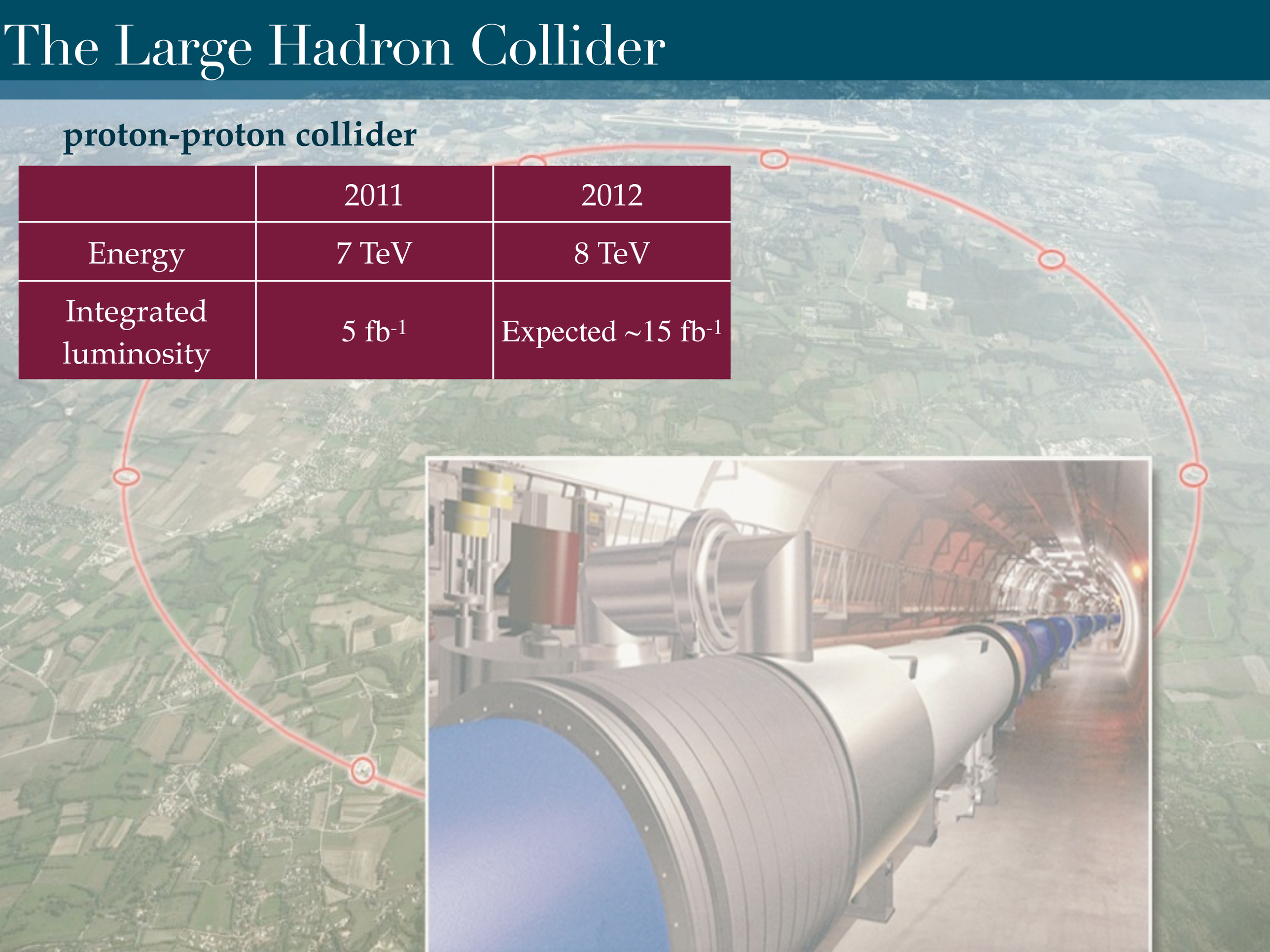


This talk!

The Large Hadron Collider

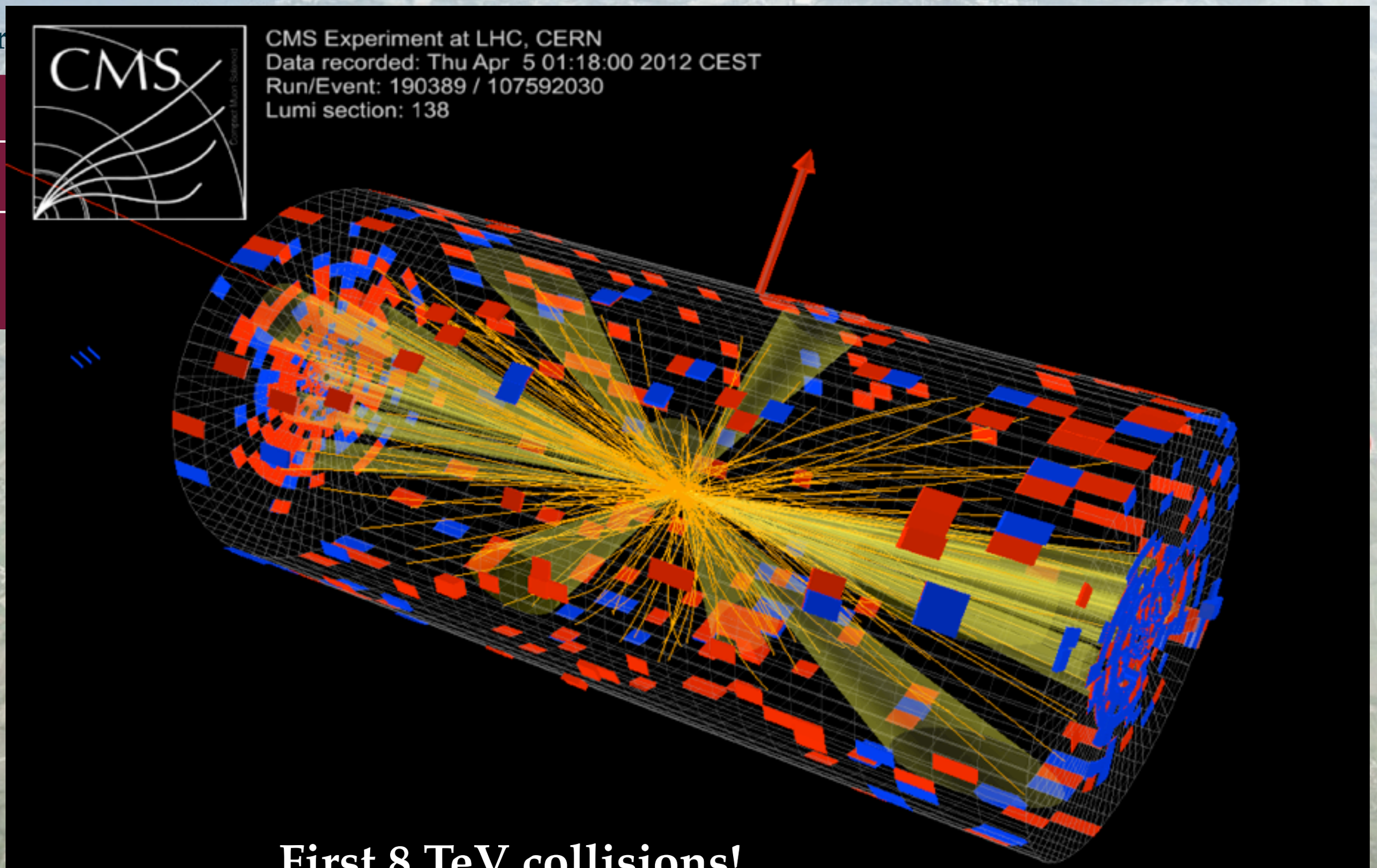
proton-proton collider

	2011	2012
Energy	7 TeV	8 TeV
Integrated luminosity	5 fb^{-1}	Expected ~15 fb^{-1}



The Large Hadron Collider

pr

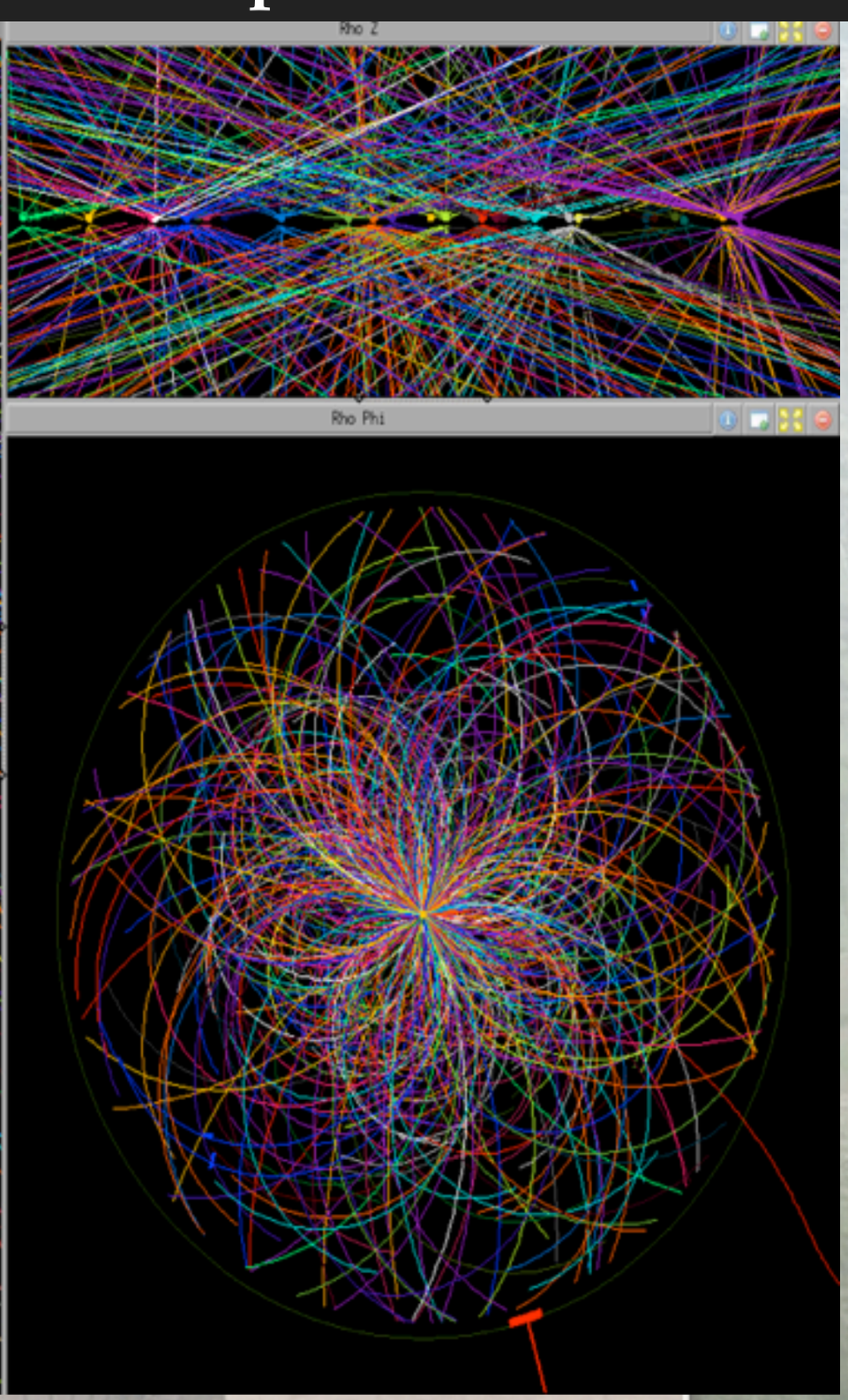


First 8 TeV collisions!

~ 27 pp interactions per bunch crossing

The Large Hadron C

Event with 29 pp interactions
Looking for 2 DM particles in this!



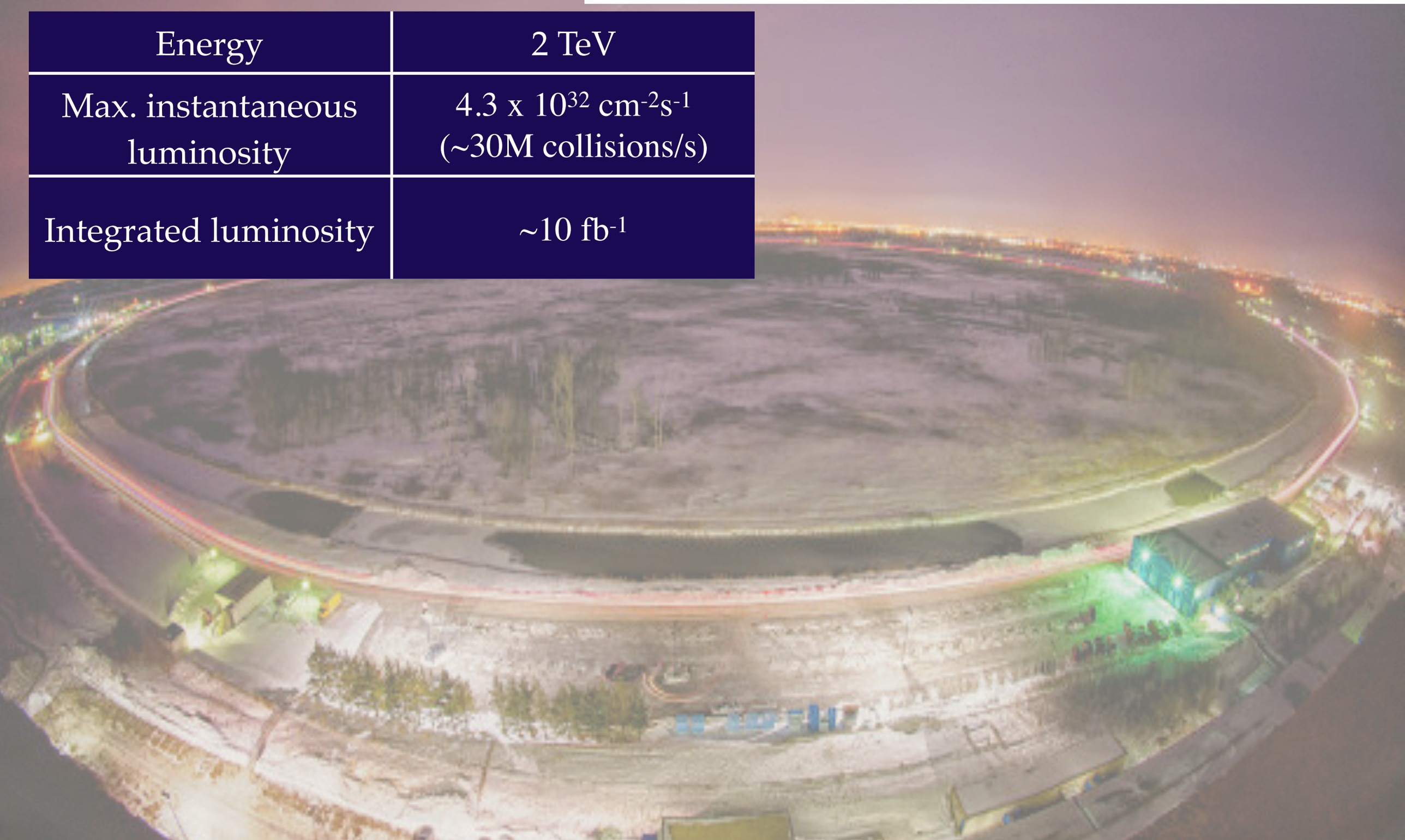
The Tevatron

proton-antiproton collider

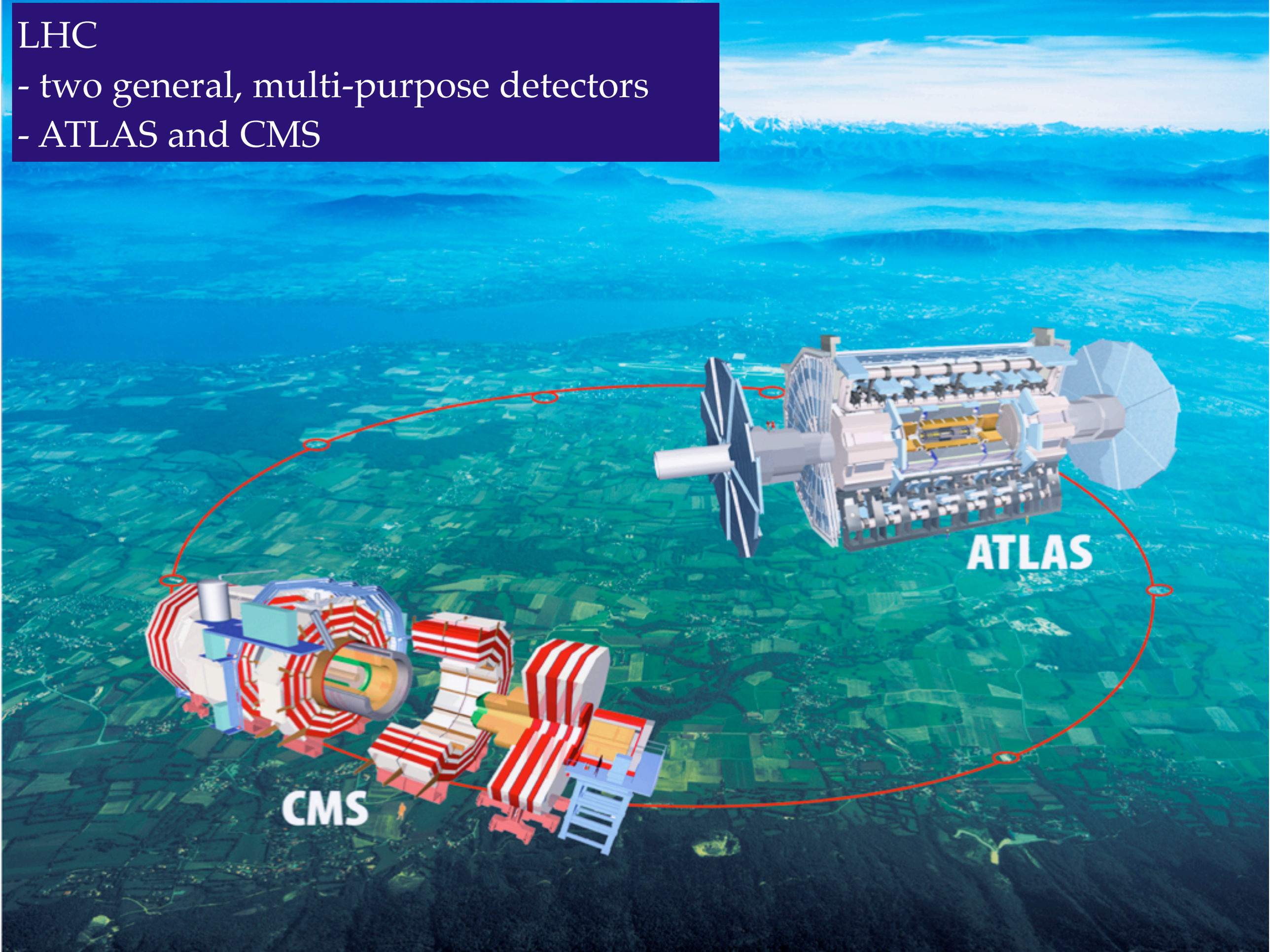
30 September 2011 Last updated at 18:08 ET

Tevatron atom smasher shuts after more than 25 years

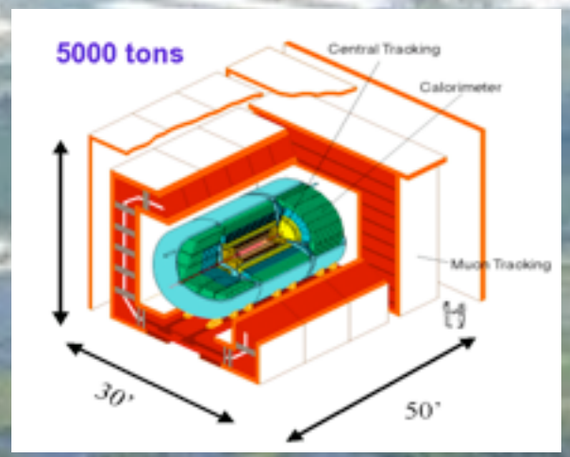
Energy	2 TeV
Max. instantaneous luminosity	4.3 x 10^{32} $cm^{-2}s^{-1}$ (~30M collisions/s)
Integrated luminosity	~10 fb^{-1}



LHC
- two general, multi-purpose detectors
- ATLAS and CMS

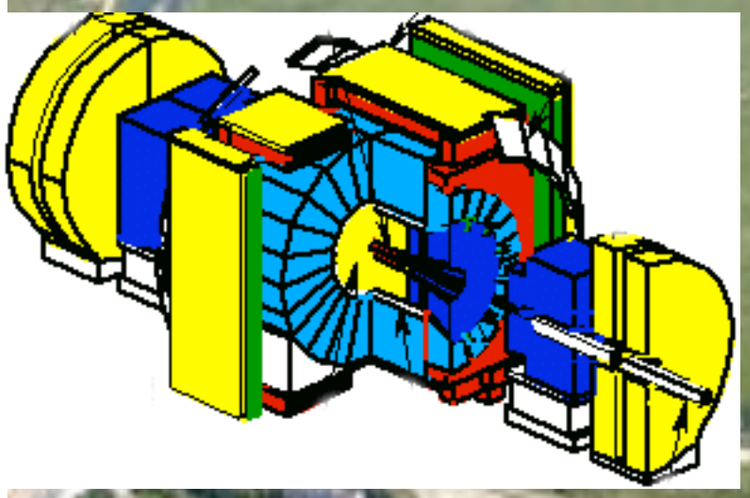


Tevatron
- two general, multi-purpose detectors
- CDF and D0

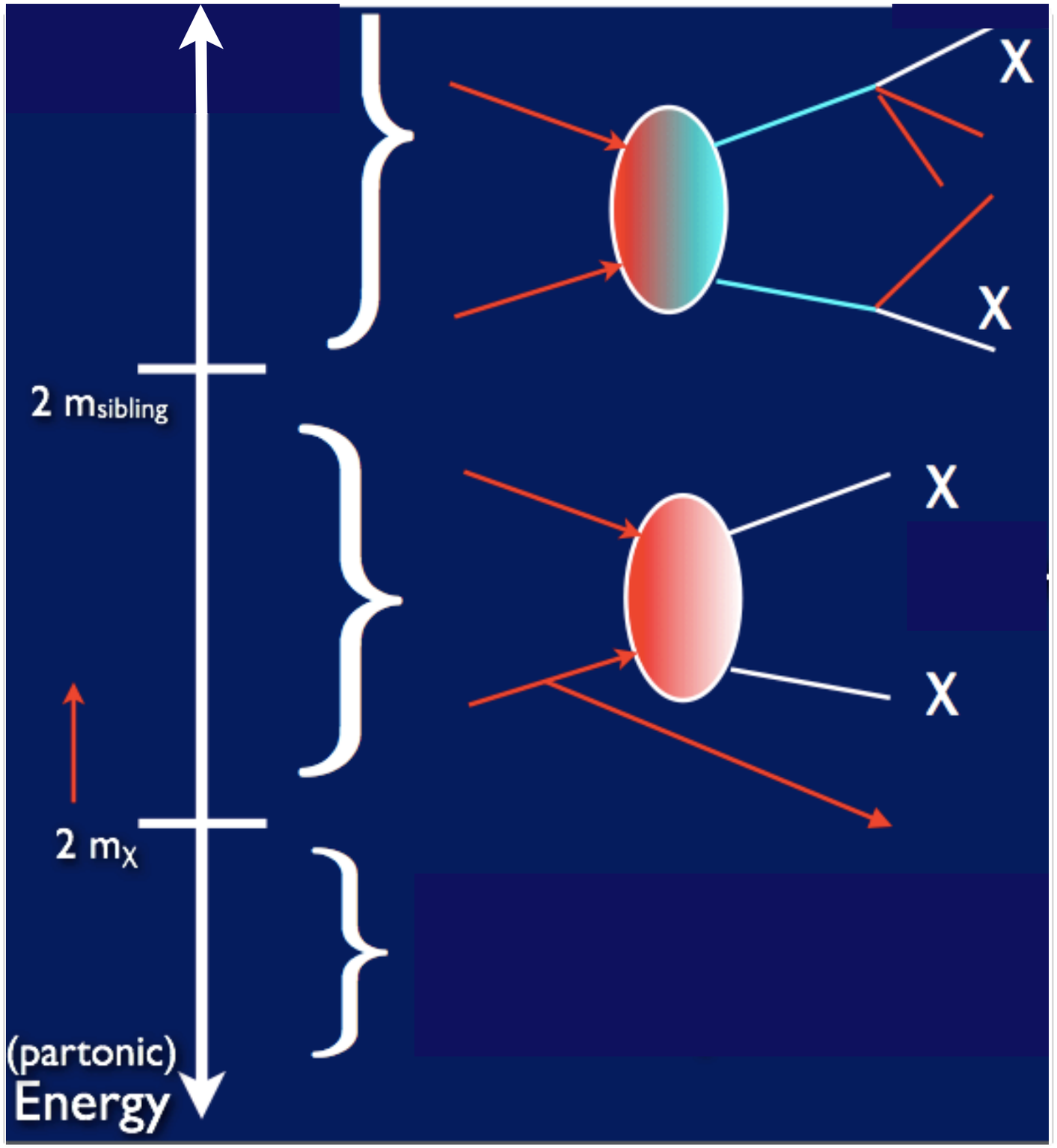


D0

CDF



Searching for dark matter at colliders



LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

Slide adapted from Tim Tait talk at Moriond

Missing Transverse Energy

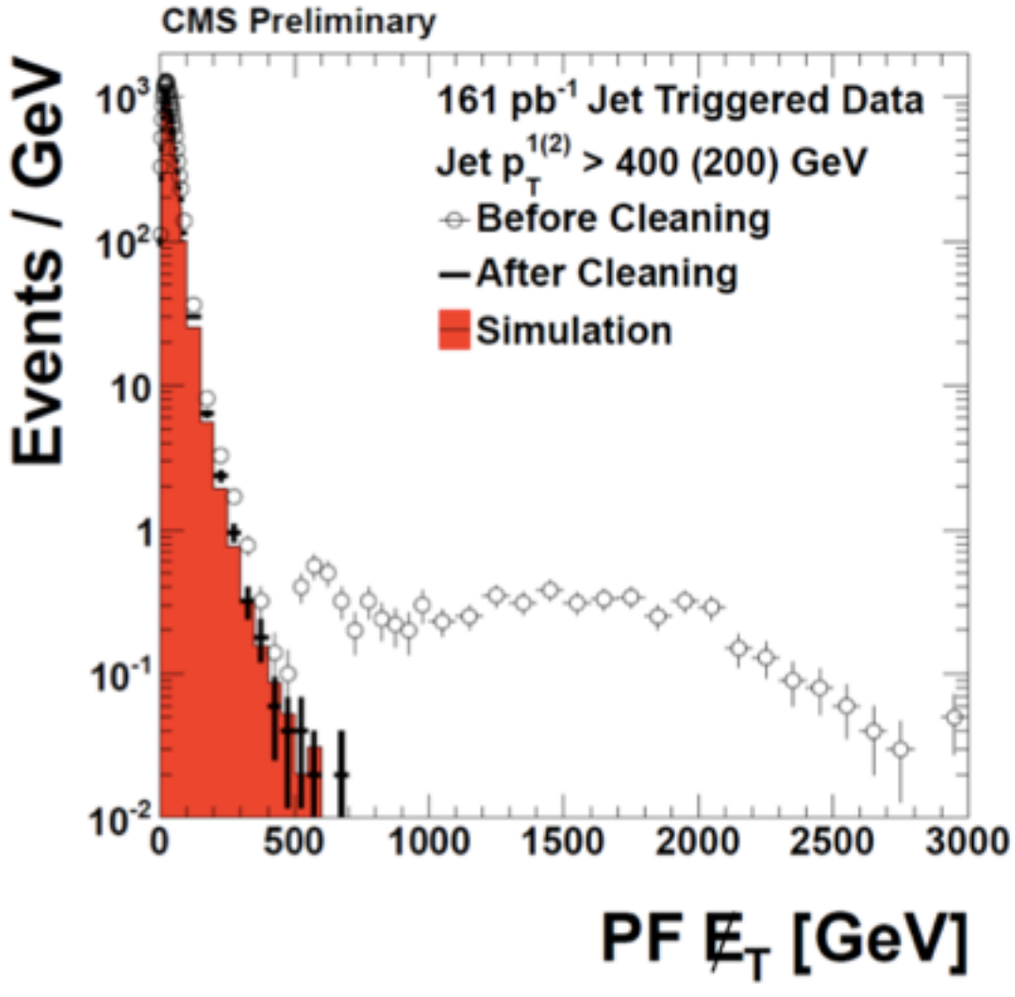
At the heart of all DM searches at colliders : Missing transverse energy (MET)

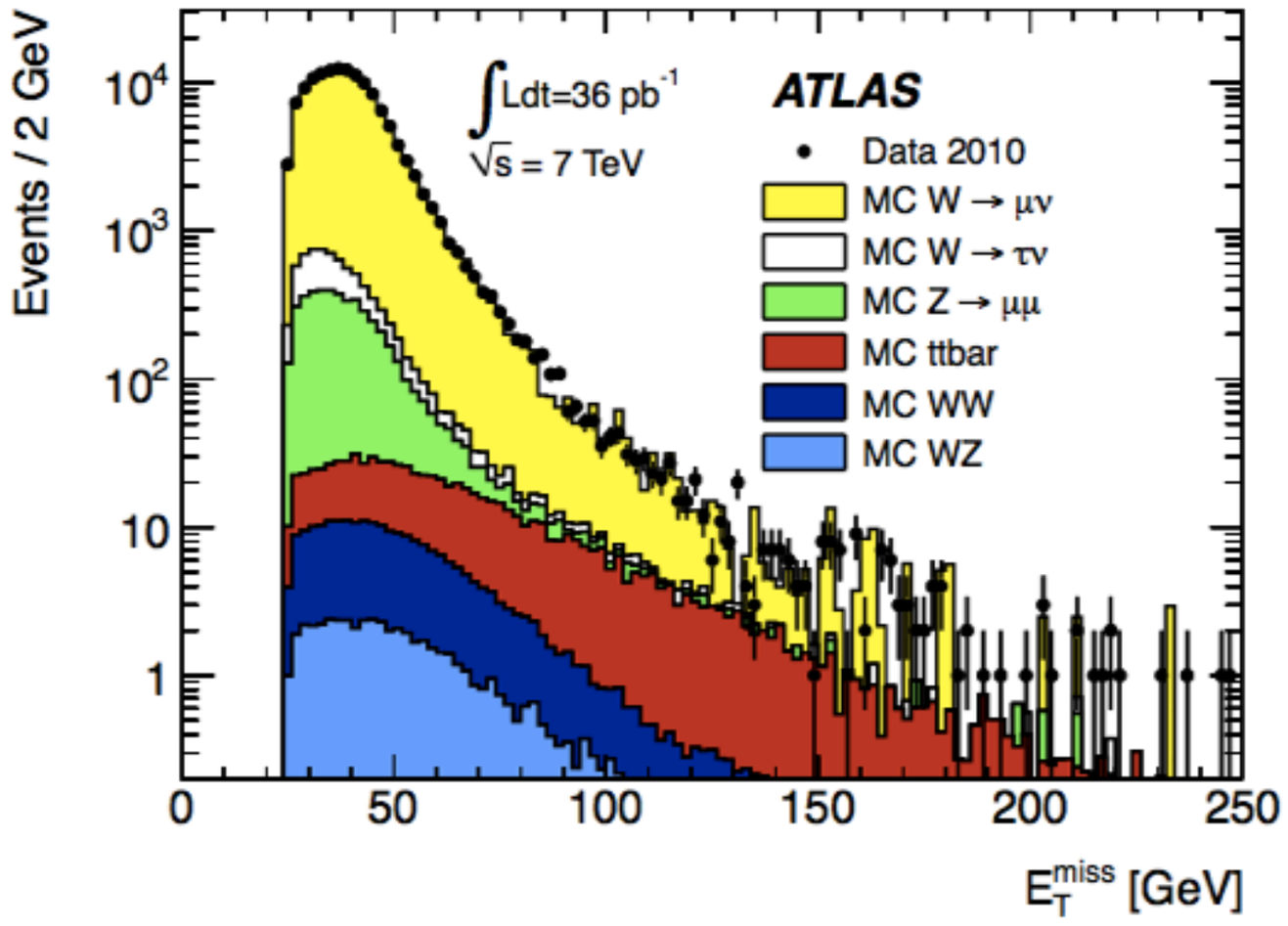
- challenging quantity to measure

- sensitive to mis-measurements, detector effects, backgrounds

- but well controlled in both ATLAS and CMS

- higher luminosity---> multiple interactions within the same bunch crossing ---> measurement of MET more challenging





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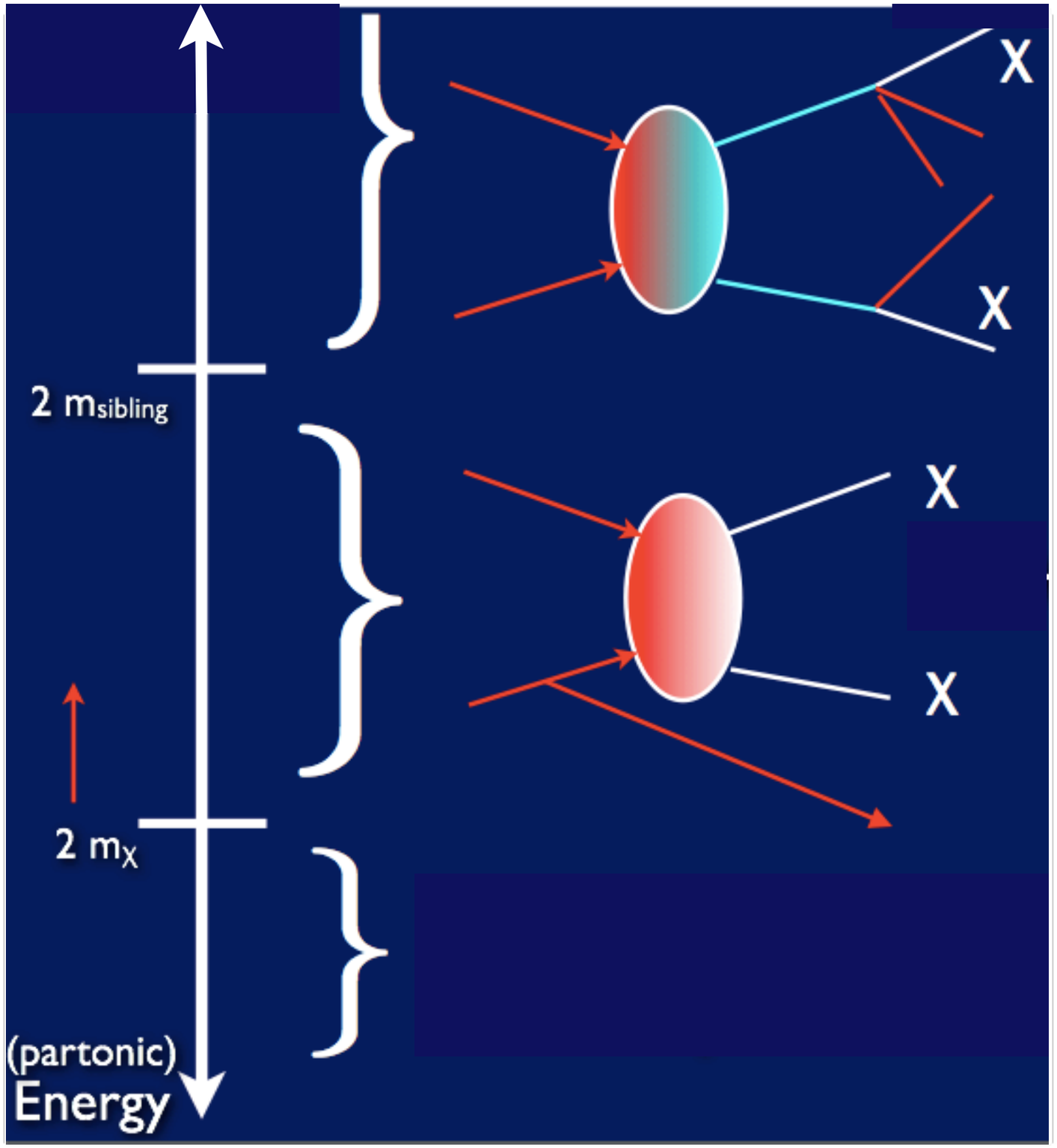

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DM candidates in new physics models

Supersymmetry

- additional symmetry between fermions and bosons
- heavy super-partners for each SM particle
- lightest SUSY particle (LSP) is neutral, stable. Good candidate for dark matter

Extra dimensions

-In UED, the dark matter candidate is a massive vector particle which is stable
- In Randall-Sundrum, the right-handed neutrino is stable
- Both theories produce WIMPs thermally in the correct abundance if the WIMP mass is at the TeV scale.

Other models with DM candidate
- variants of technicolor models

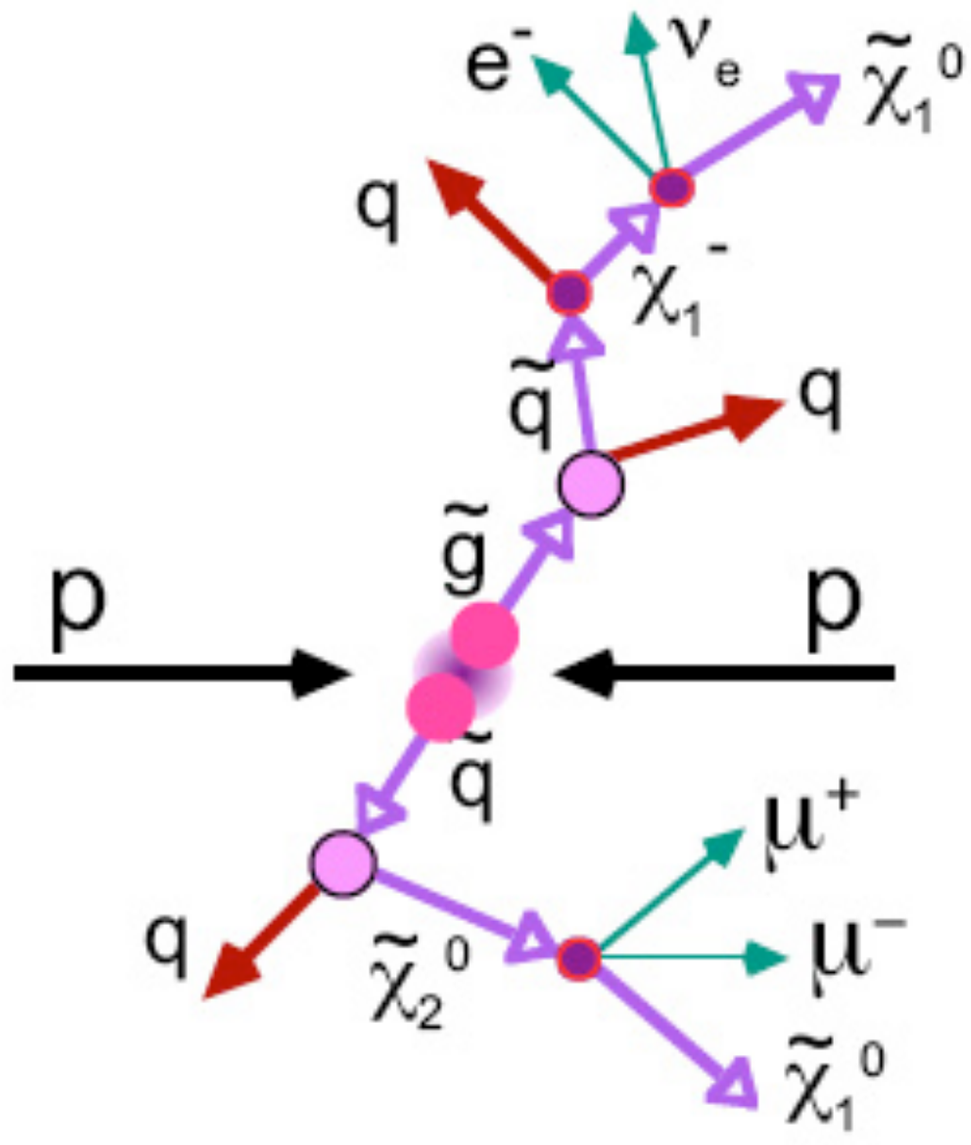
Supersymmetry

R-parity conservation - the lightest SUSY particle is stable, good candidate for dark matter; neutralino, gravitino

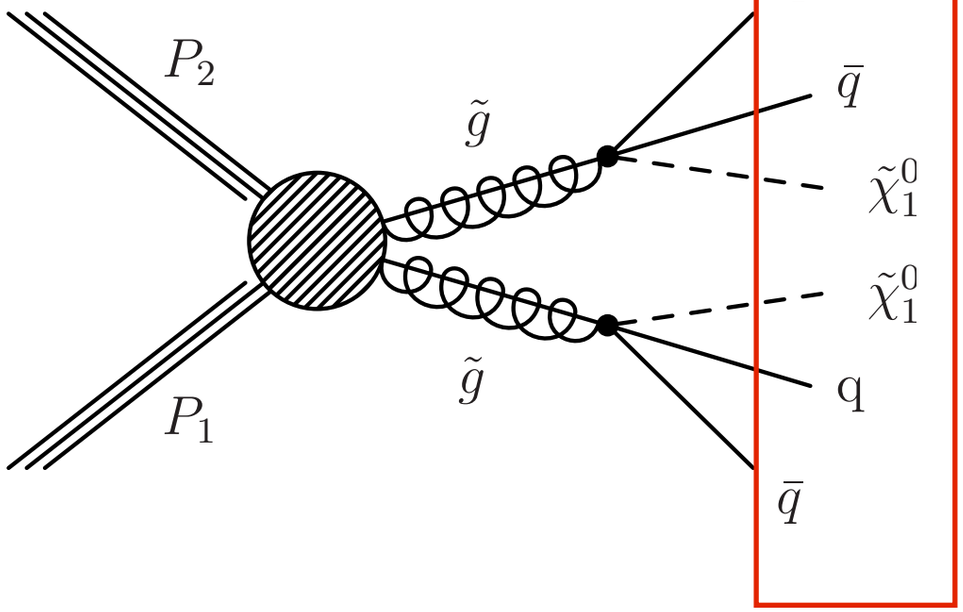
- can use NLSP decay to tune relic density

- signatures include jets, Met, leptons, photons.

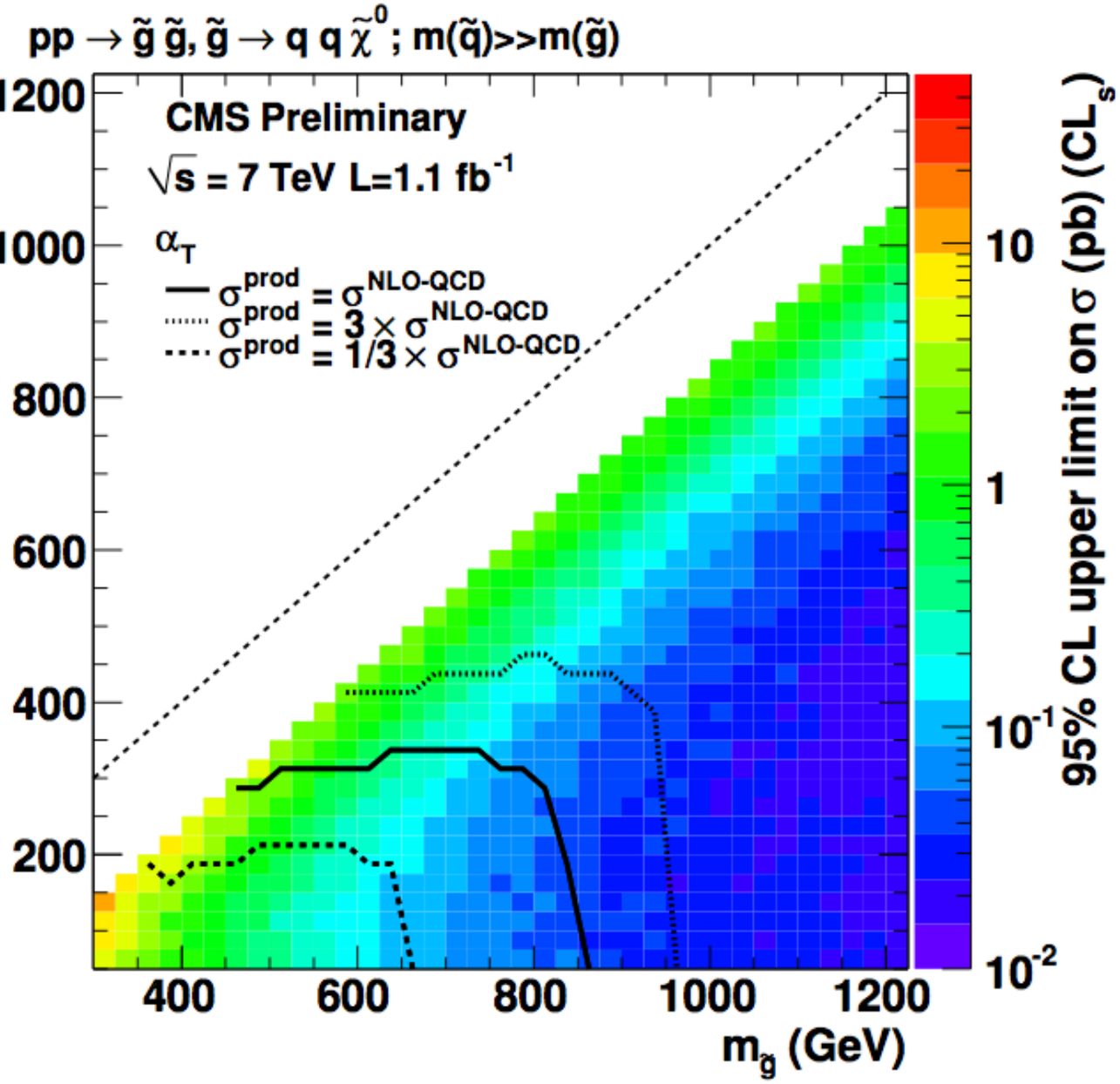
- jets +Met most generic channel



Searches for SUSY



Jets and missing energy in final state



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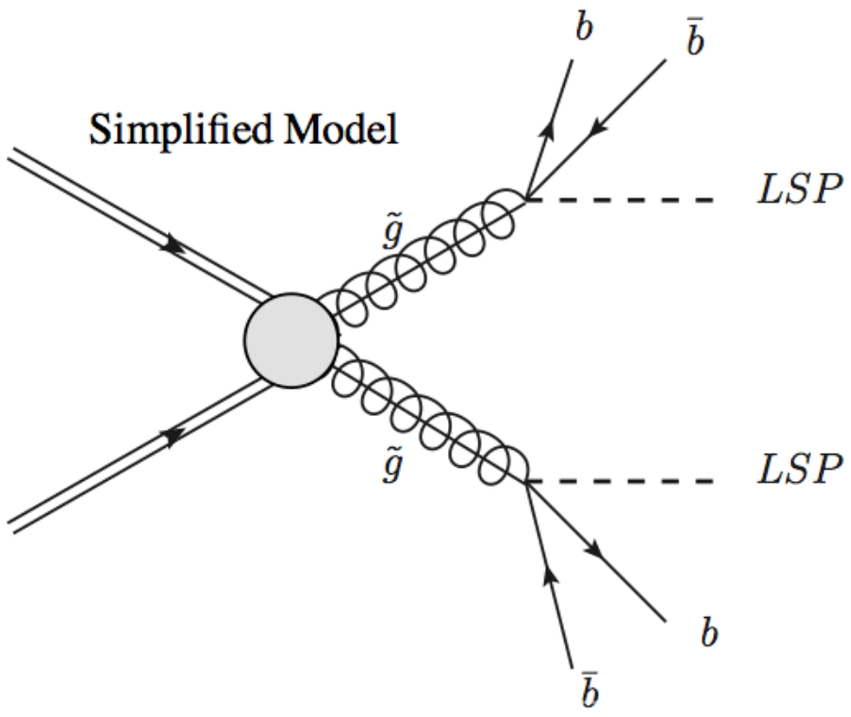
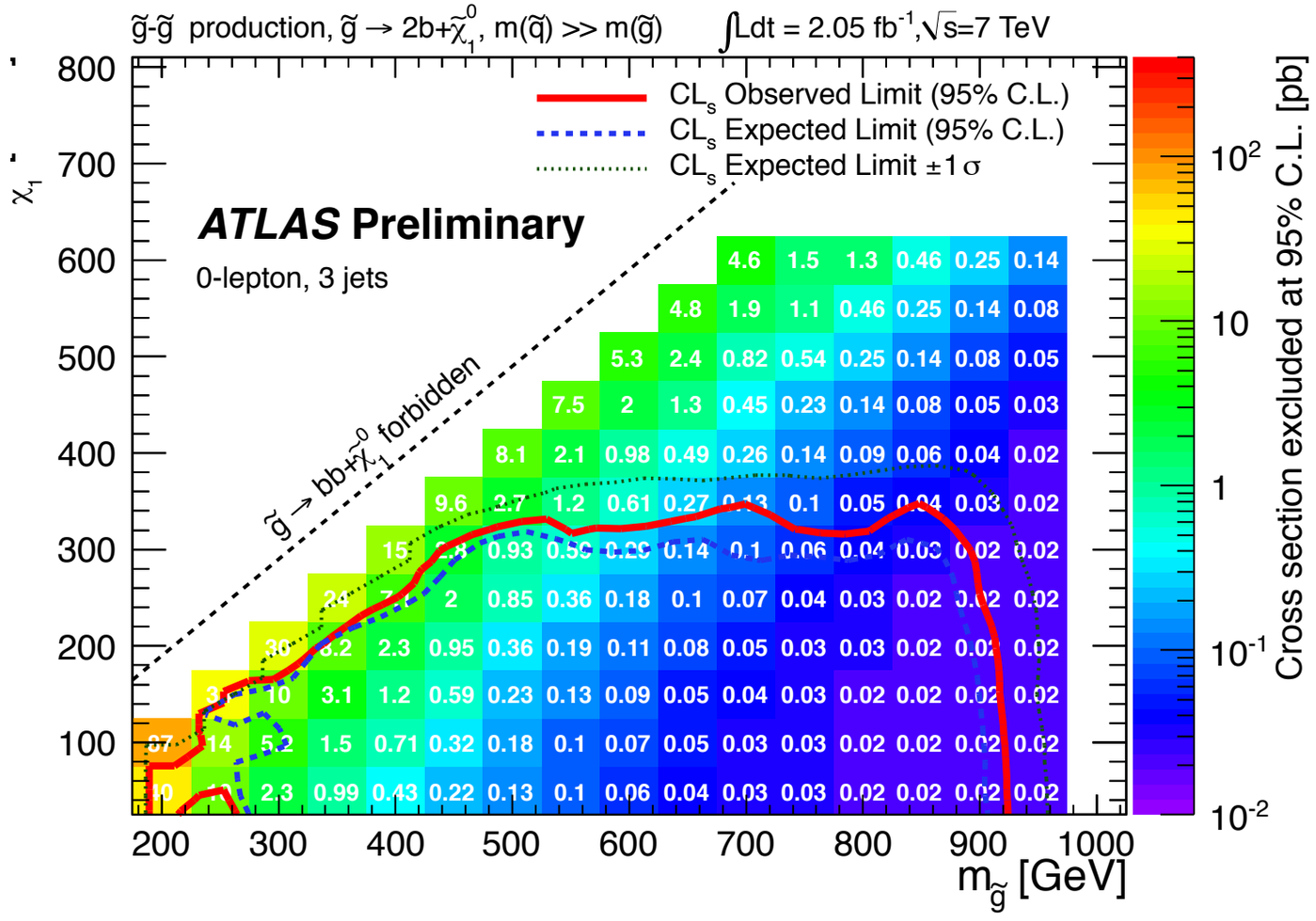
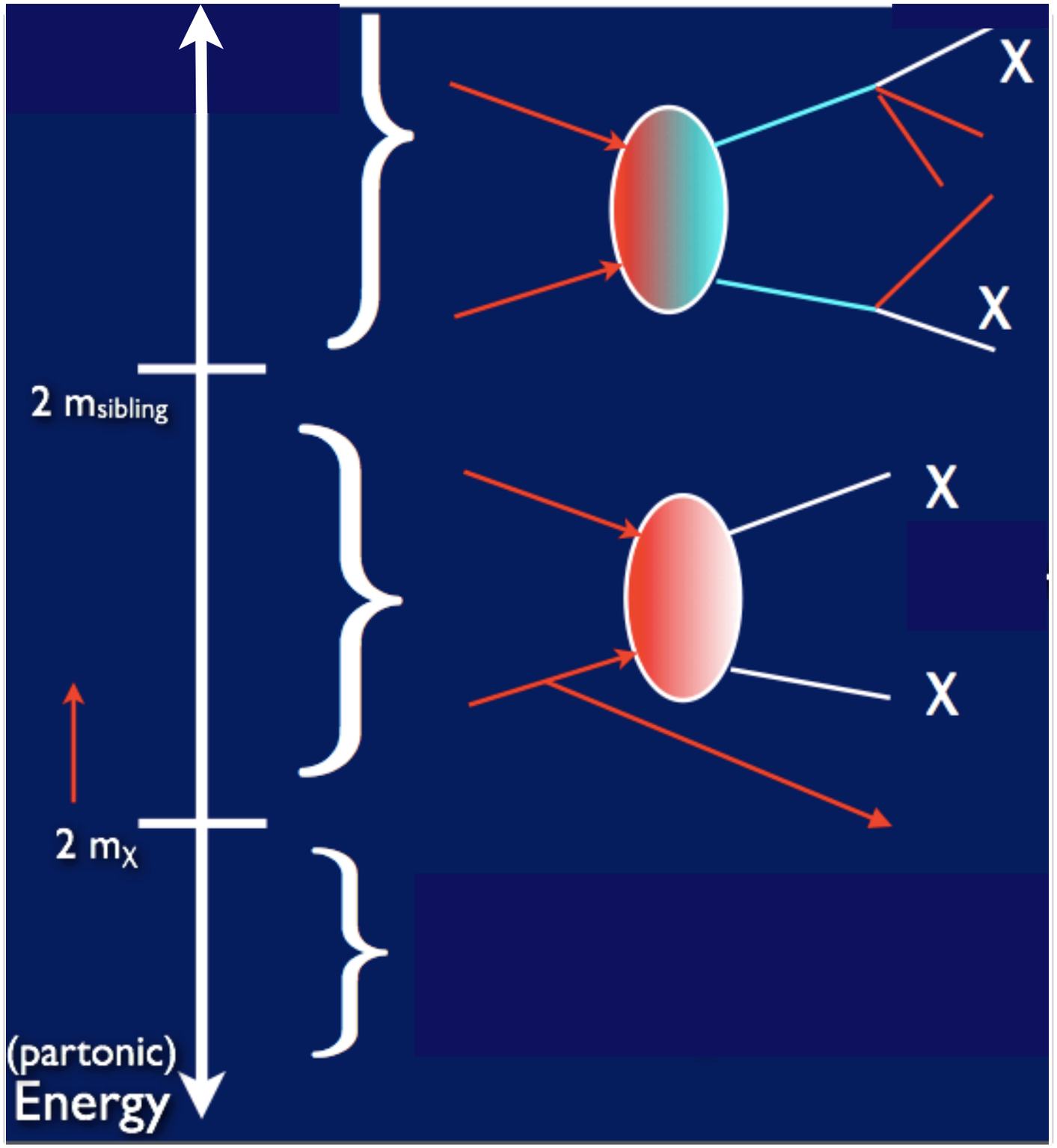




Gluino masses below 900 GeV are excluded for neutralino masses up to about 300 GeV

Searching for dark matter at colliders



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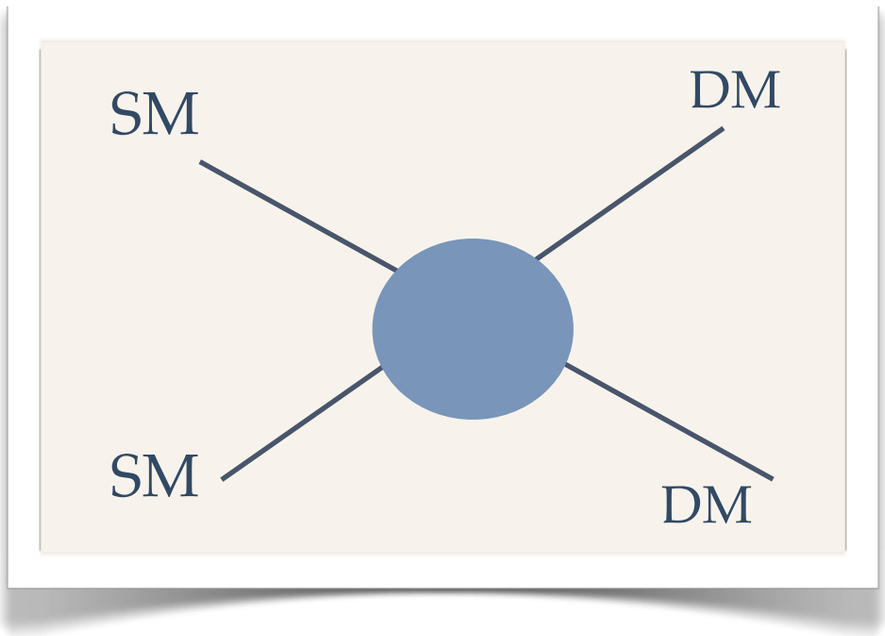
Recent studies

1. Beltran,Hooper,Kolb,Krusberg,Tait, 1002.4137
2. Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1005.1286
3. Bai, Fox, Harnik, 1005.3797
4. Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1008.1783
5. Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1009.0008
6. Fox, Harnik, Kopp,Tsai, 1103.0240
7. Fortin,Tait, 1103.3289
8. Cheung,Tseng,Yuan, 1104.5329
9. Shoemaker,Vecchi, 1112.5457
10. Haipeng An, Xiangdong Ji, Lian-Tao Wang

Phenomenology

Assumptions:
- DM particle is only new state accessible to the collider
- Effective field theory so interaction between DM and SM particles is contact interaction
- Mediator can be integrated out



$$\mathcal{L} = \mathcal{L}_{SM} + \underbrace{i\bar{X}\gamma^{\mu}\partial_{\mu}X - M_X\bar{X}X}_{\text{kinetic terms for DM}} + \underbrace{\sum_{q}\sum_{i,j}\frac{G_{qij}}{\sqrt{2}}\left[\bar{X}\Gamma_i^X X\right]\left[\bar{q}\Gamma_q^j q\right]}_{\text{set of 4-Fermion interactions between DM and SM quarks}},$$

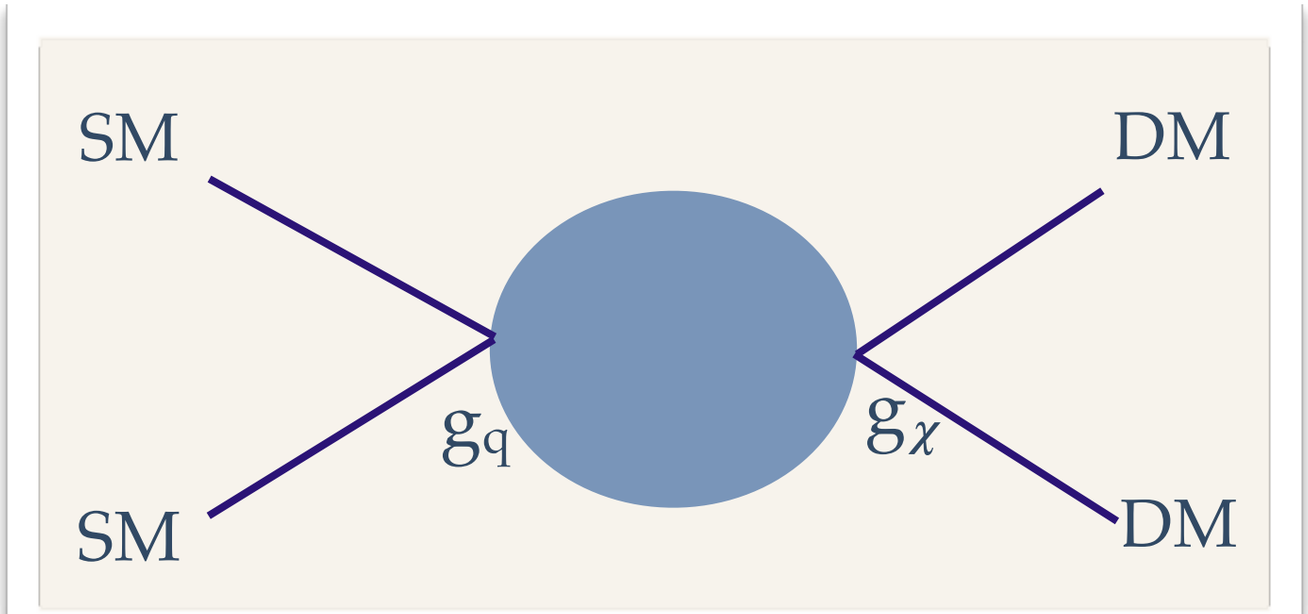
SM Lagrangian

Operators $\mathbf{\Gamma}$ describe scalar, pseudoscalar, vector, axial vector, tensor interactions

Phenomenology

Assume DM is a Dirac fermion and interaction is characterized by contact interaction,

Bai, Fox and Harnik,
JHEP 1012:048 (2010)



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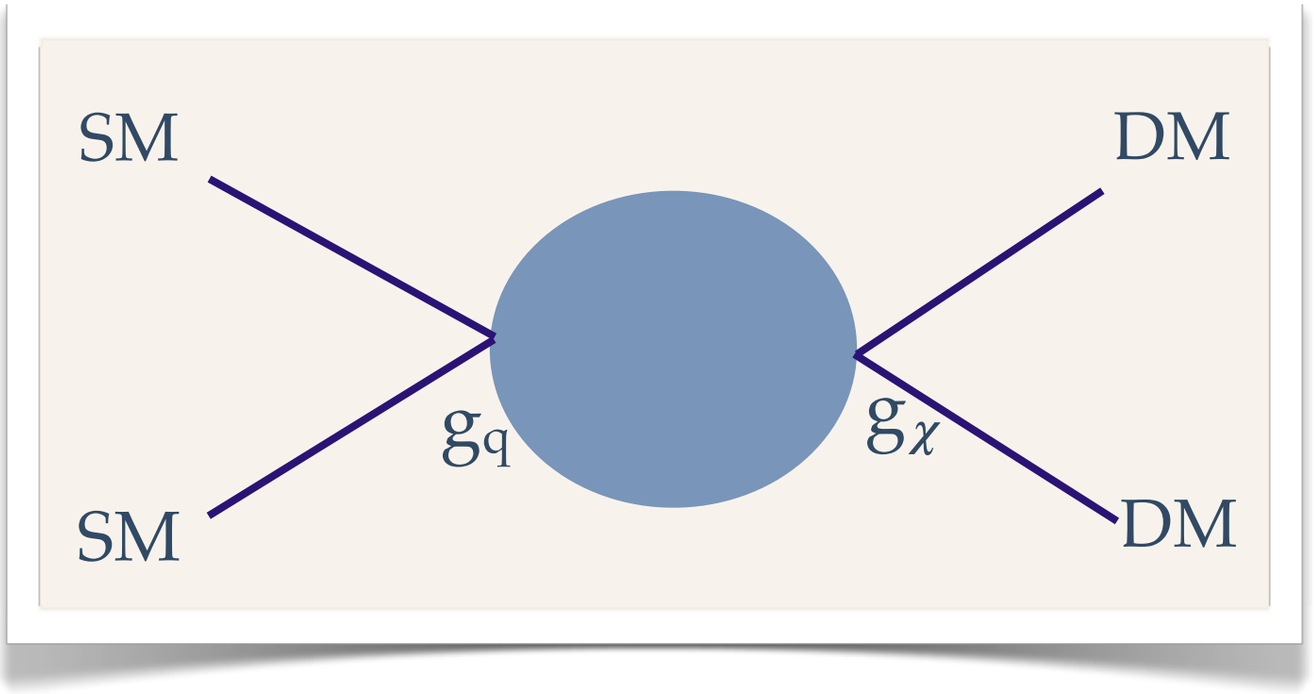
Assume DM is a Dirac fermion and interaction is characterized by contact interaction,

Bai, Fox and Harnik, JHEP 1012:048 (2010)

Set mass of mediator (M) to very high value



Operators describe nature of mediator and form of SM-DM couplings.

Consider two possibilities:

(a) vector operator

(b) axial-vector operator

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Bai, Fox and Harnik, JHEP 1012:048 (2010)

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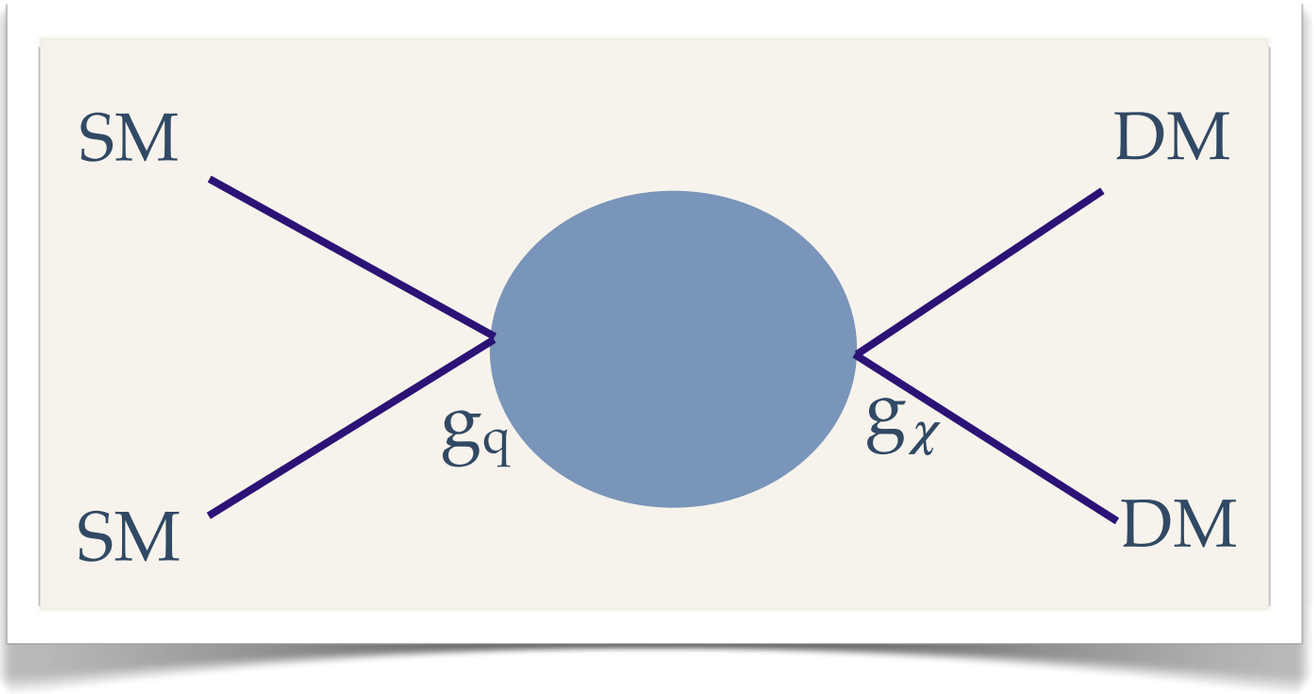

(a) For vector mediator, effective operator

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\Lambda = M/\sqrt{g_\chi g_q}$$

spin-independent

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Bai, Fox and Harnik, JHEP 1012:048 (2010)

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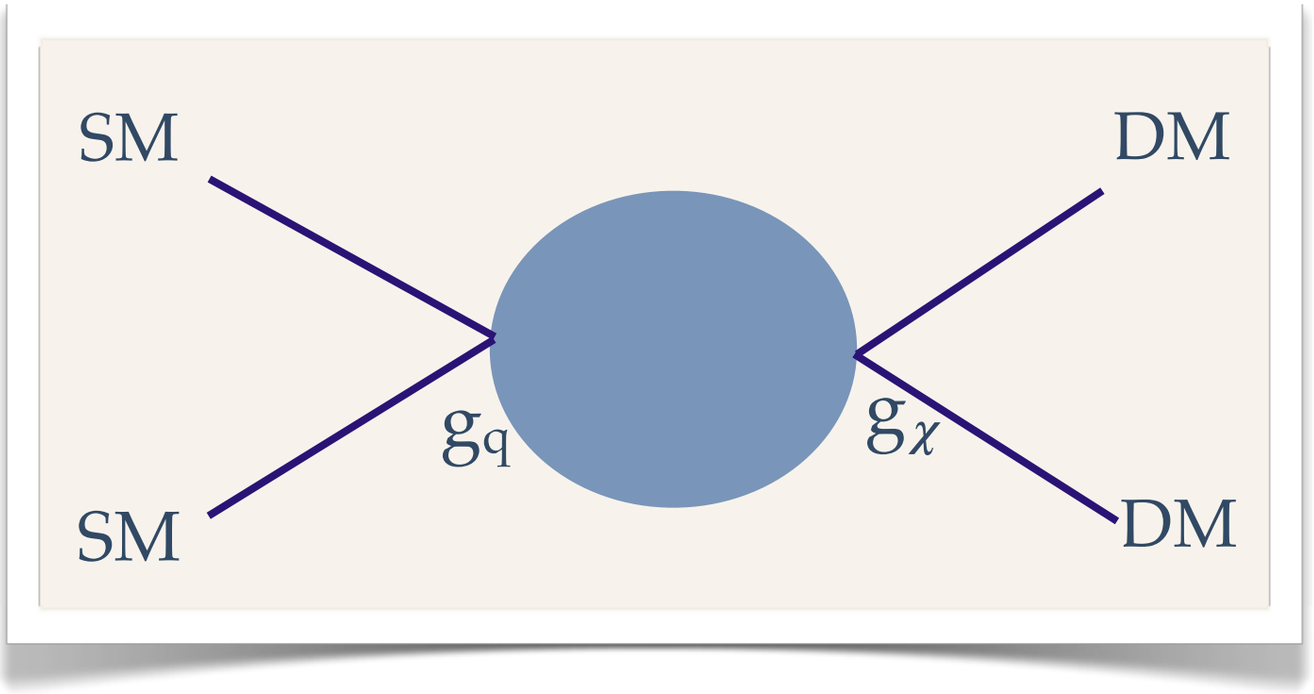


(b) For axial-vector mediator, effective operator

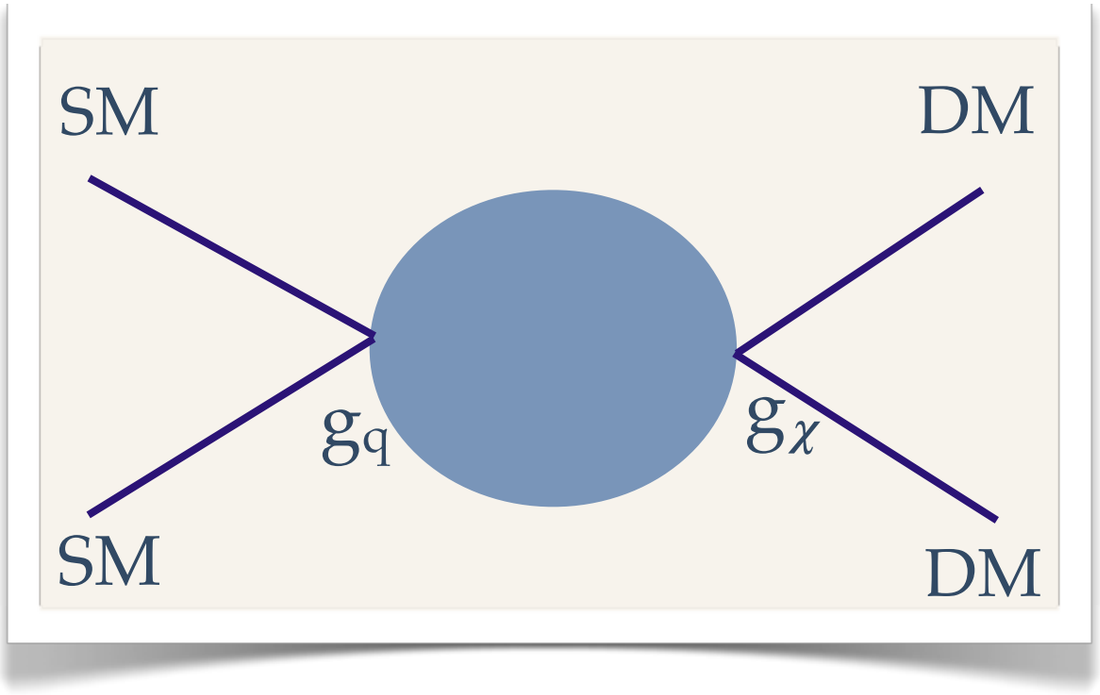
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2} \qquad \Lambda = M/\sqrt{g_\chi g_q}$$

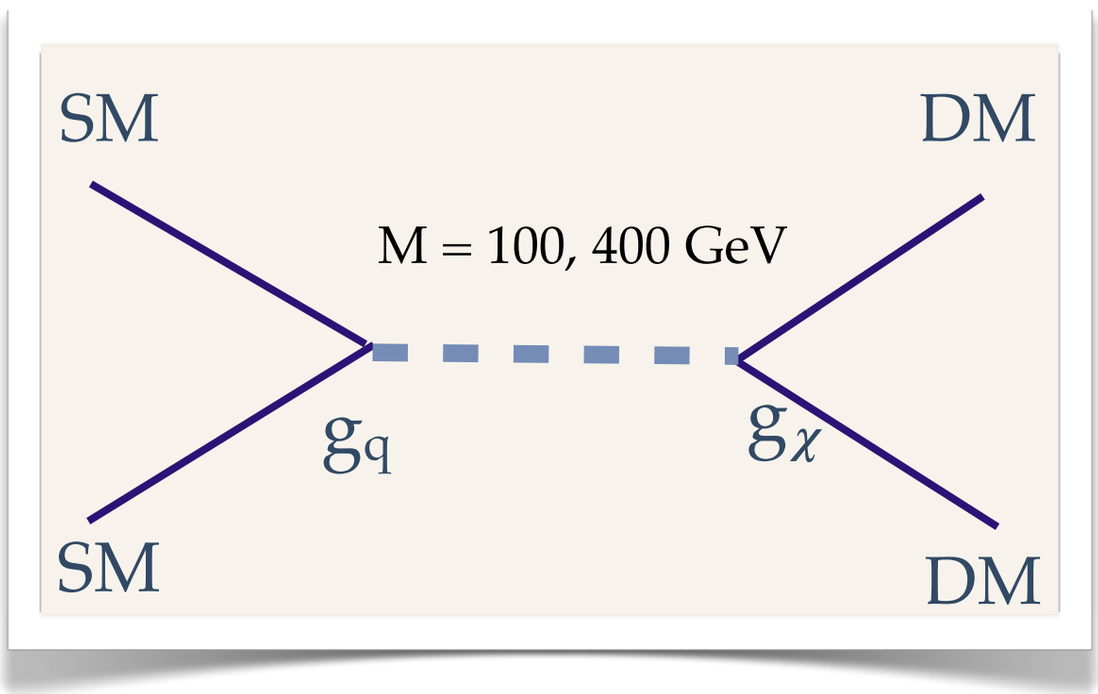
spin-dependent

Phenomenology

Light mediator

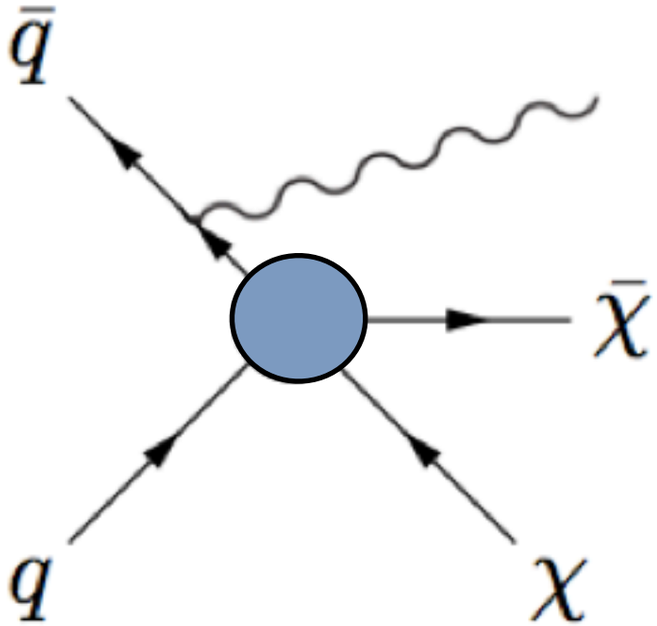
- Assume DM interaction is mediated by light particle
- Effective theory breaks down and explicitly have to include mediator mass.
- Consider M = 100 GeV, 400 GeV with width set to 1% of mass.



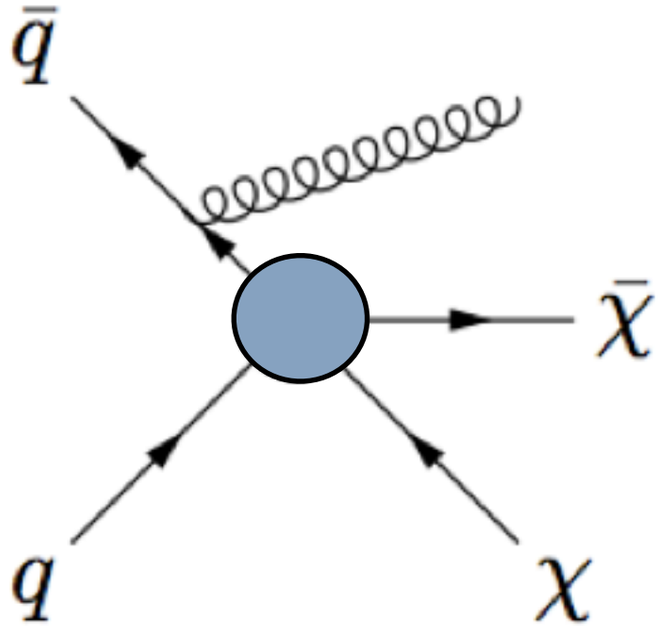


Dark matter searches

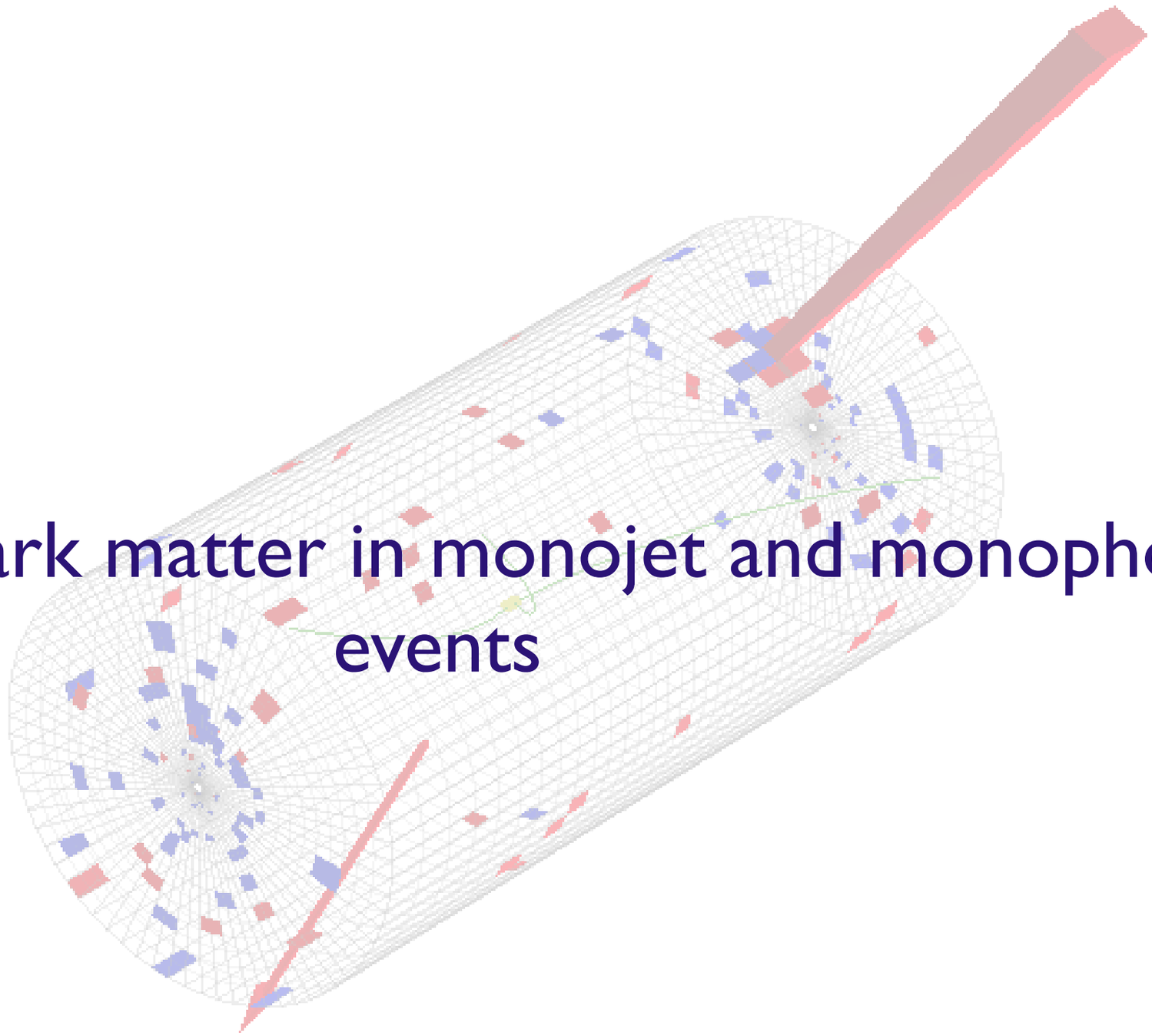
Dark matter pair production at LHC
- radiation of a photon/jet from initial state
- DM particles produce missing energy



monophoton +MET



monojet +MET



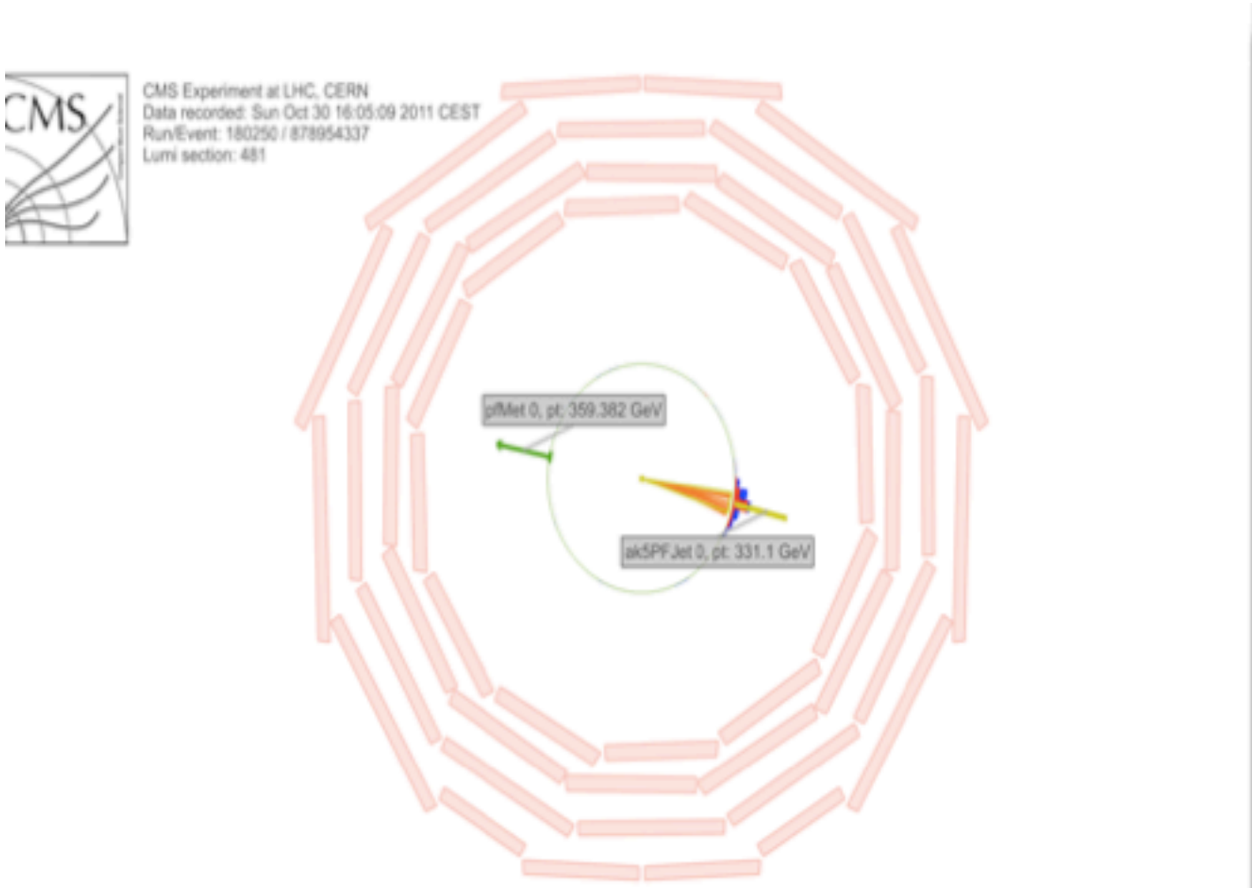
Search for dark matter in monojet and monophoton events

CMS Experiment at LHC, CERN
Data recorded: Sun Apr 24 22:57:52 2011 CDT
Run/Event: 163374 / 314736281
Lumi section: 604

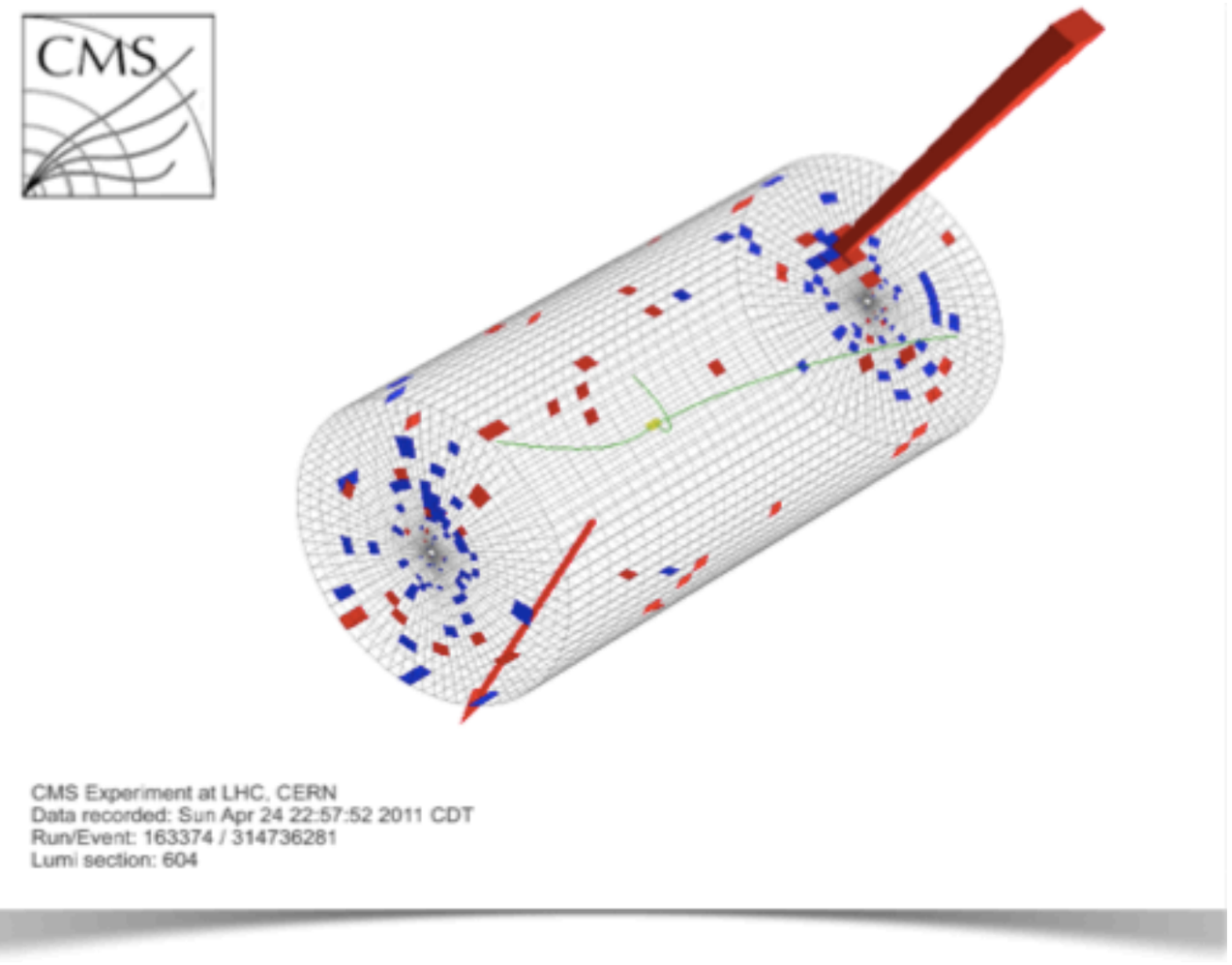
Search for dark matter in monojet and monophoton events

Simple and striking signatures

http://arxiv.org/abs/1204.0821



A monojet event,
p_T(jet) = 331 GeV, MET = 359 GeV



Highest p_T monophoton event,
p_T(photon) = 384 GeV, MET = 407 GeV

Measurement Strategy

- ‘cut and count’ : apply event selection and count number of events in signal region
- look for excess of events above those expected from SM backgrounds
- understanding of backgrounds is crucial

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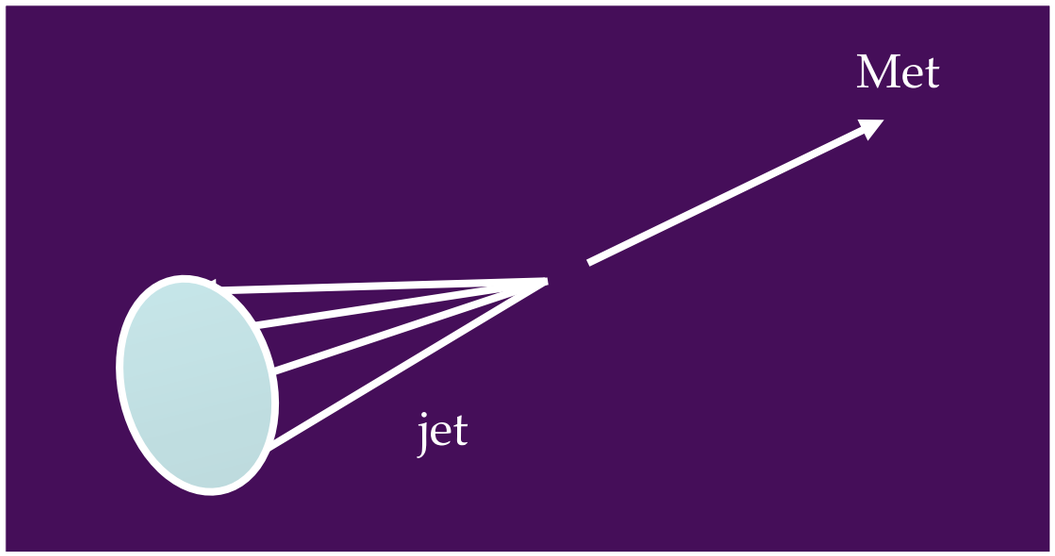

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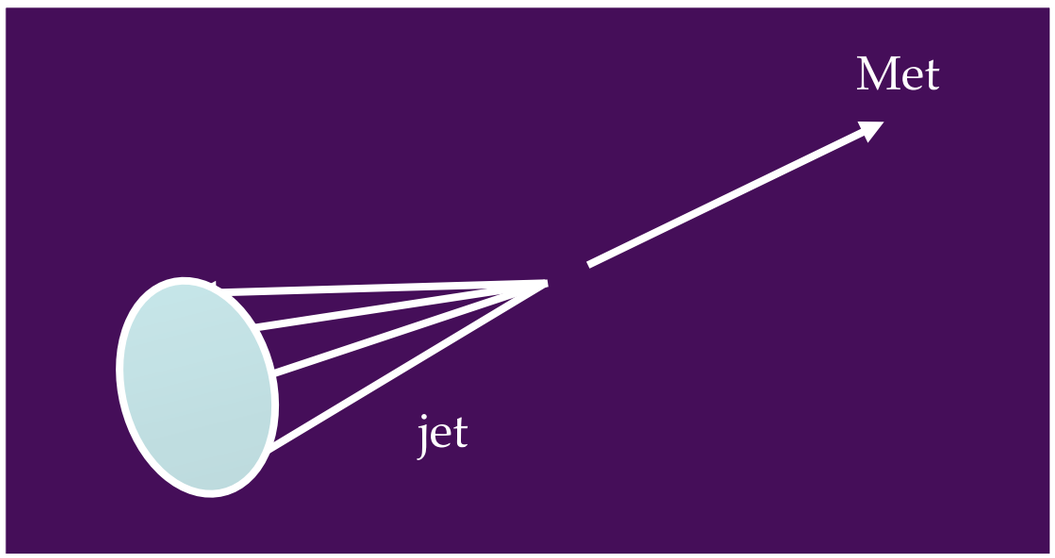
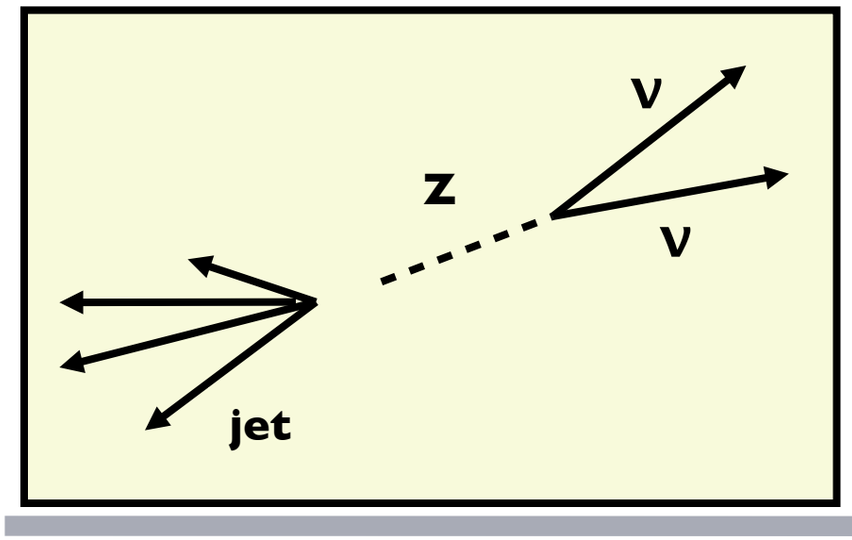


Backgrounds

Z→νν +jet, irreducible background, looks just like signal



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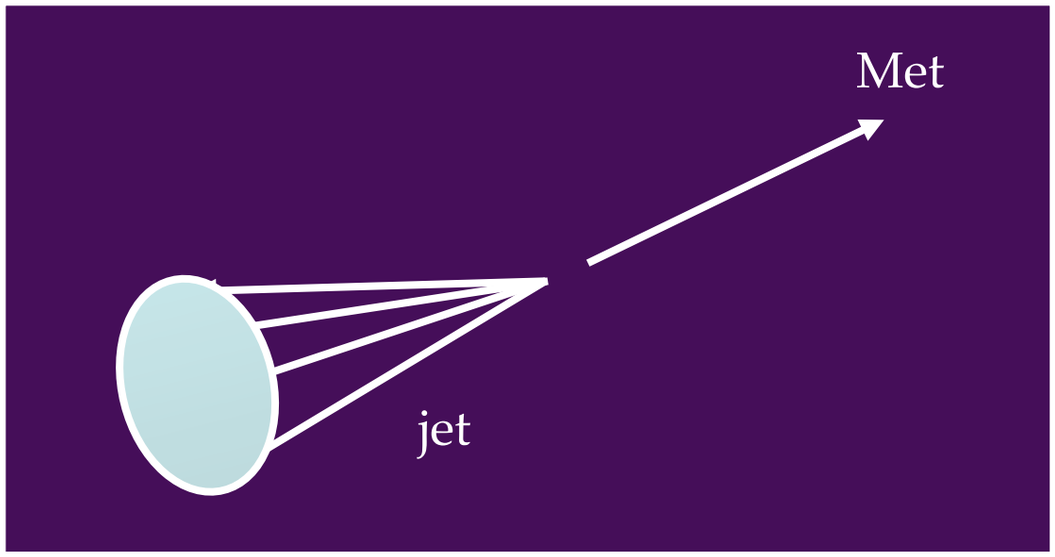

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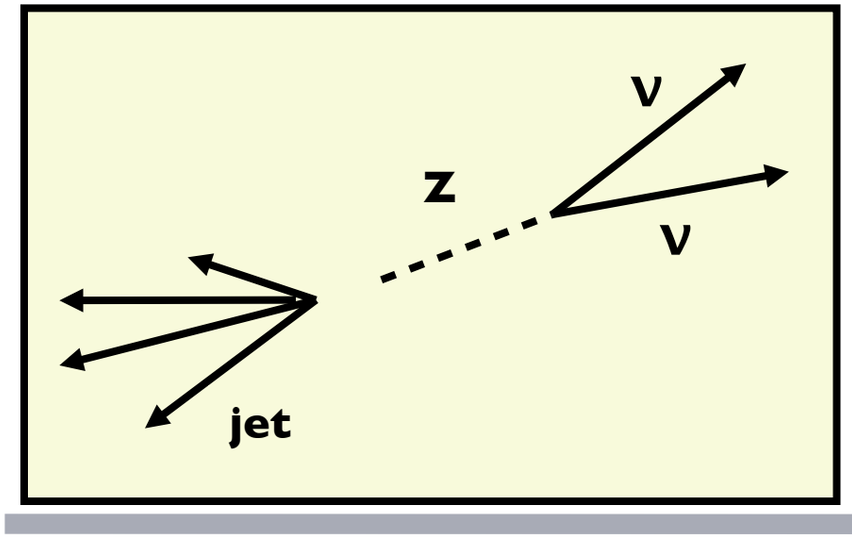
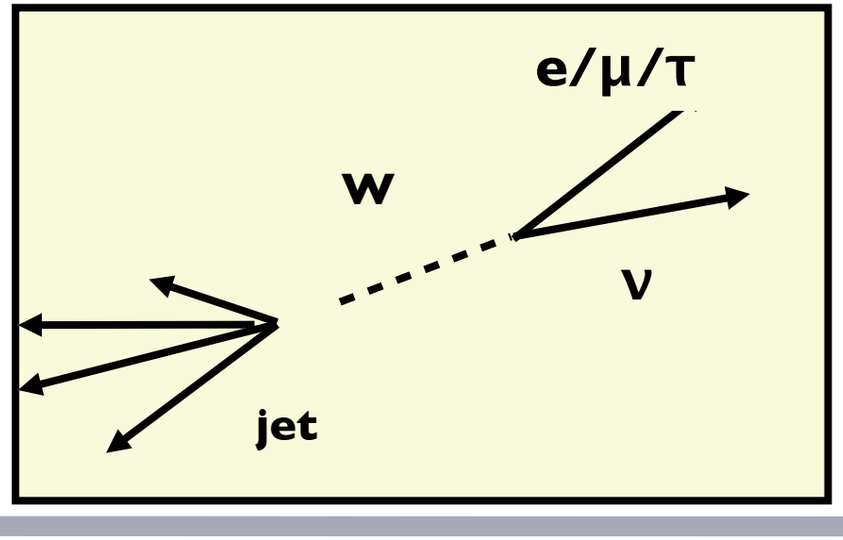


W+jets, e/u is not detected, tau decays hadronically



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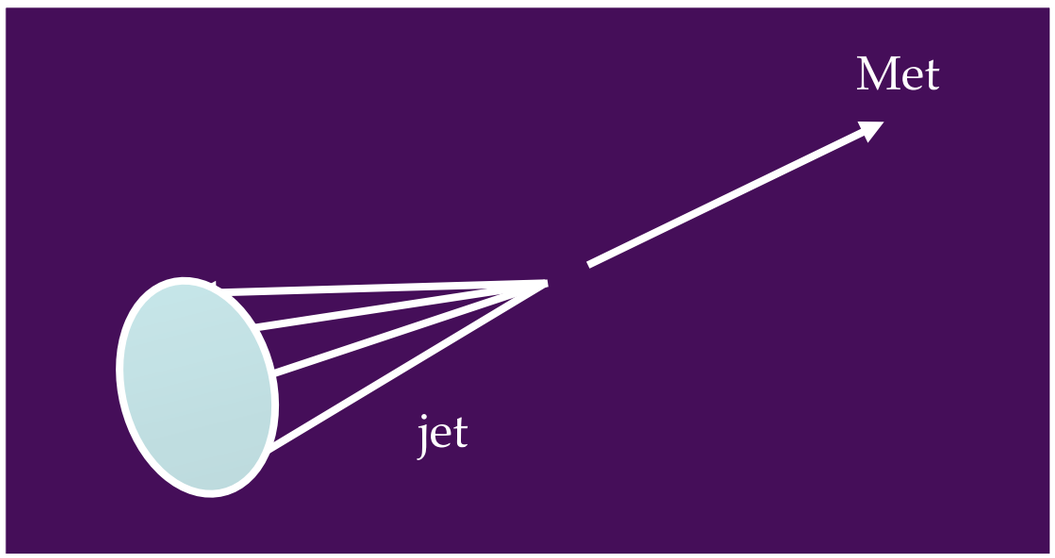

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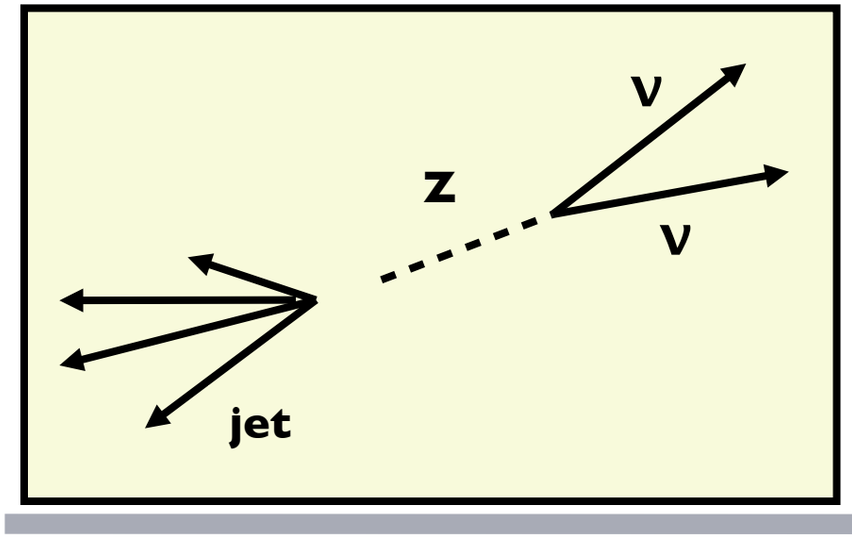

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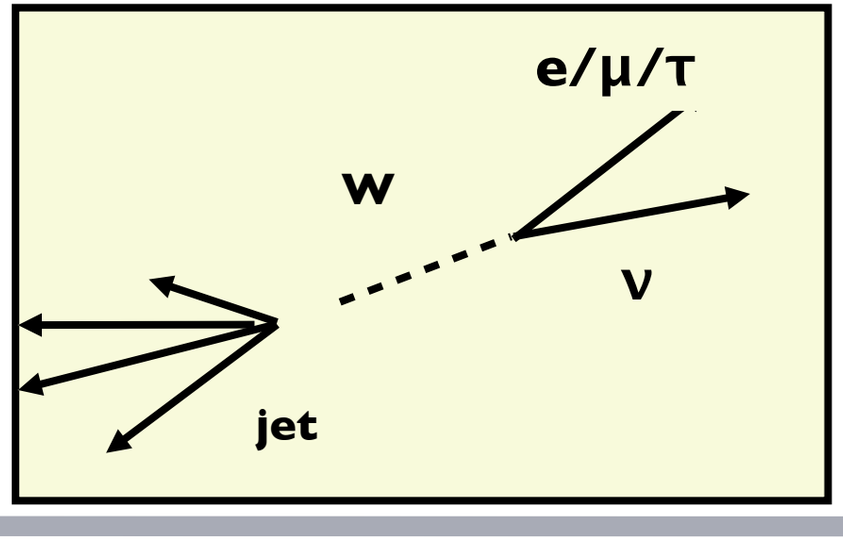
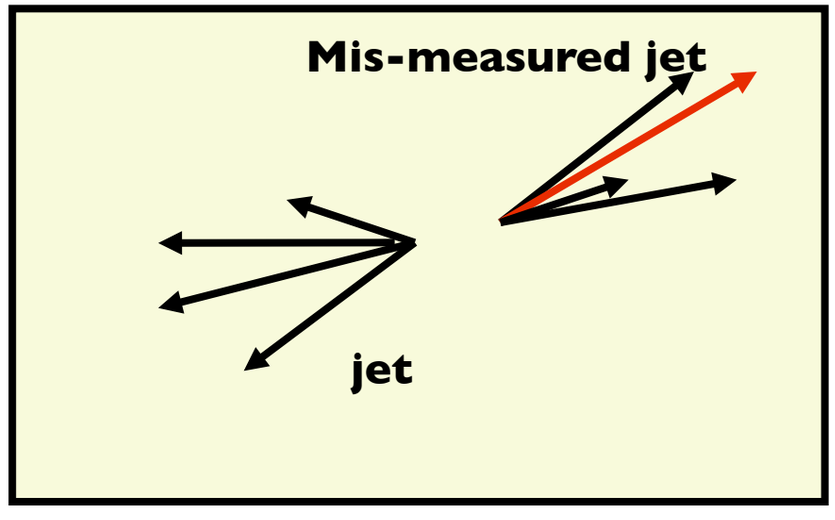


QCD, jet is mismeasured, producing Met.



Measurement Strategy

Select topology

- Large missing energy, Met > 350 GeV
- One energetic jet, p_T > 110 GeV, $|\eta| < 2.4$
- Veto event if it has more than 2 jets (with p_T > 30 GeV)

Reject background

• QCD

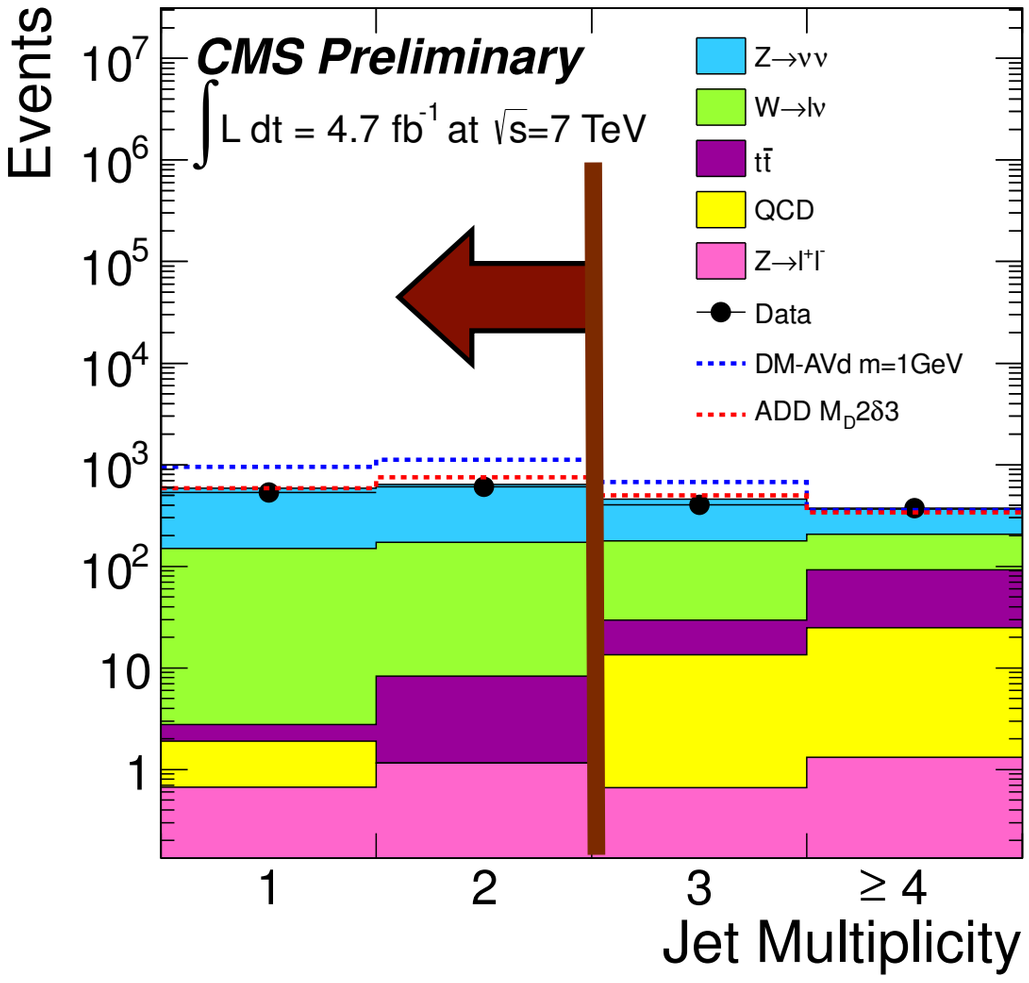
- $\Delta\varphi(j1,j2) > 2.5$

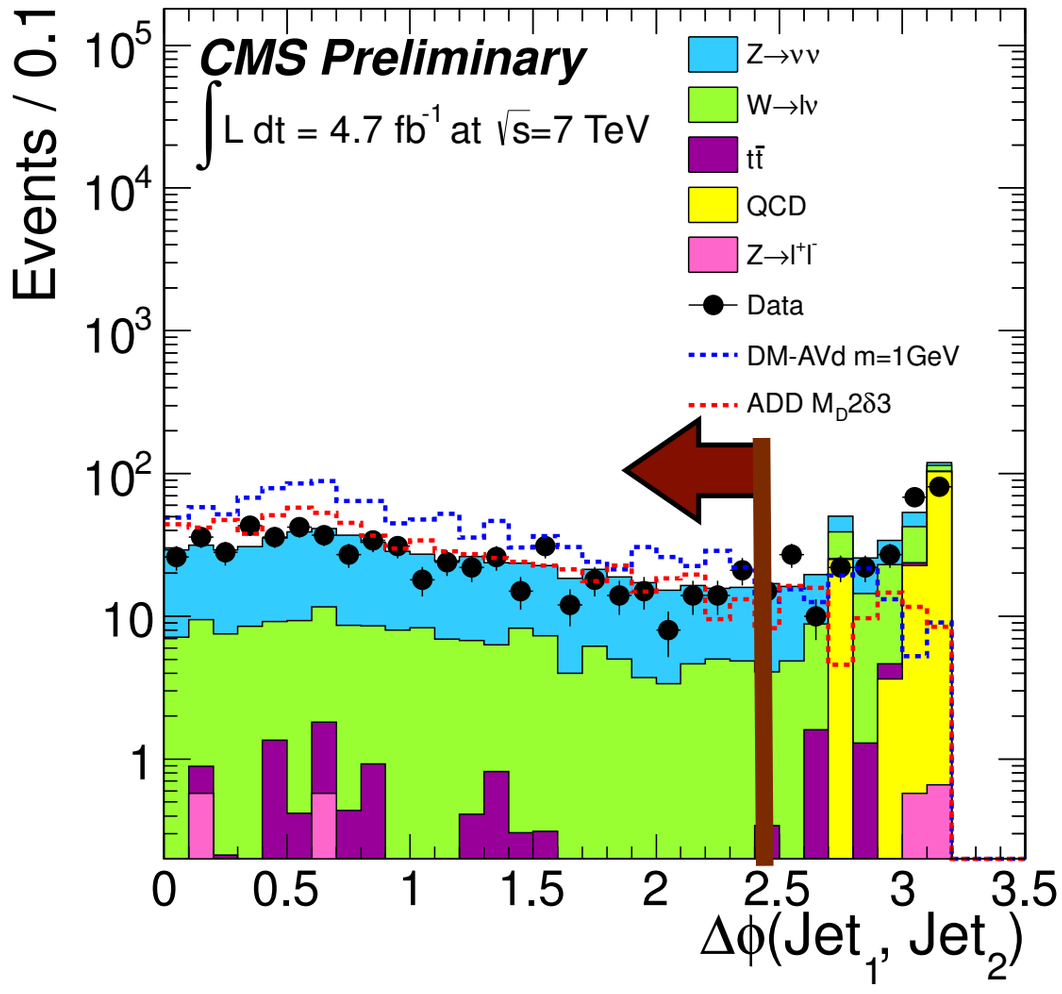
-remove events with back to back jets

• EWK

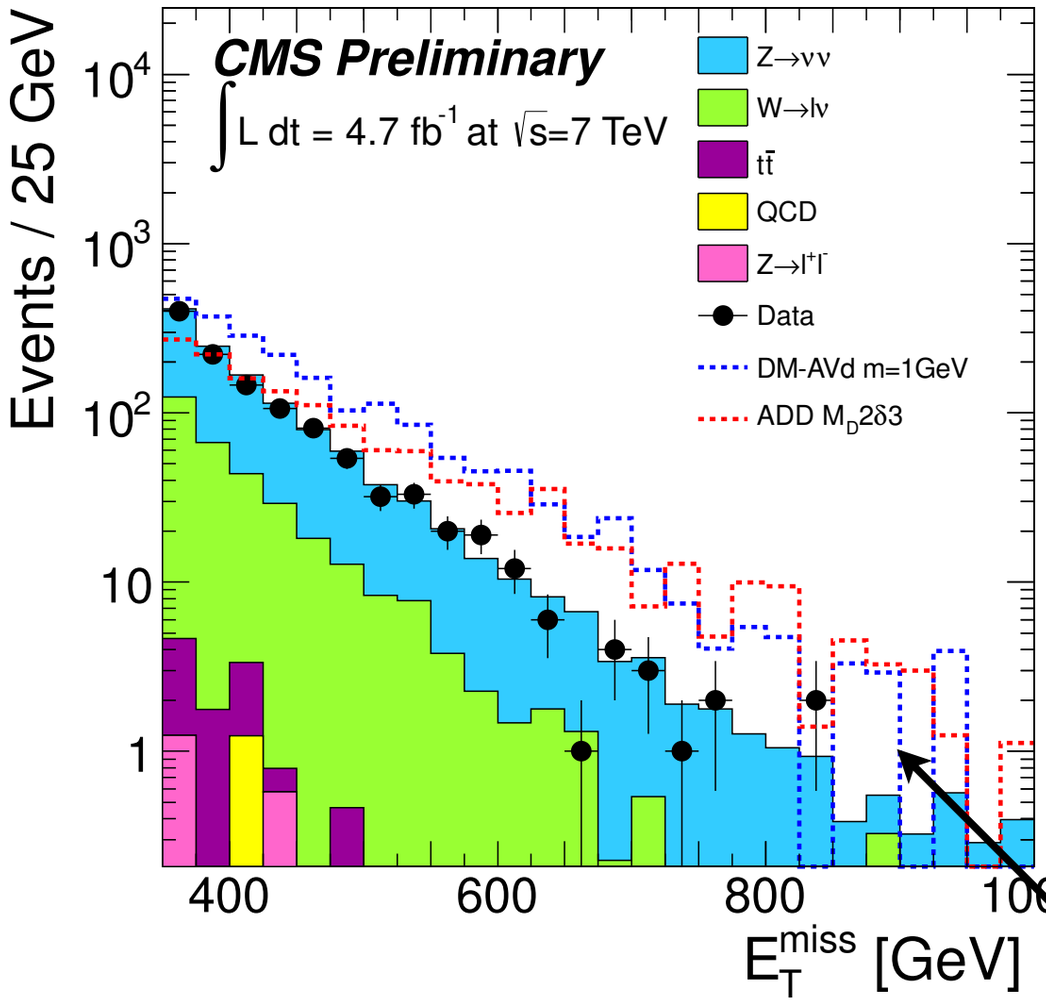
-reject events with isolated electrons, muons

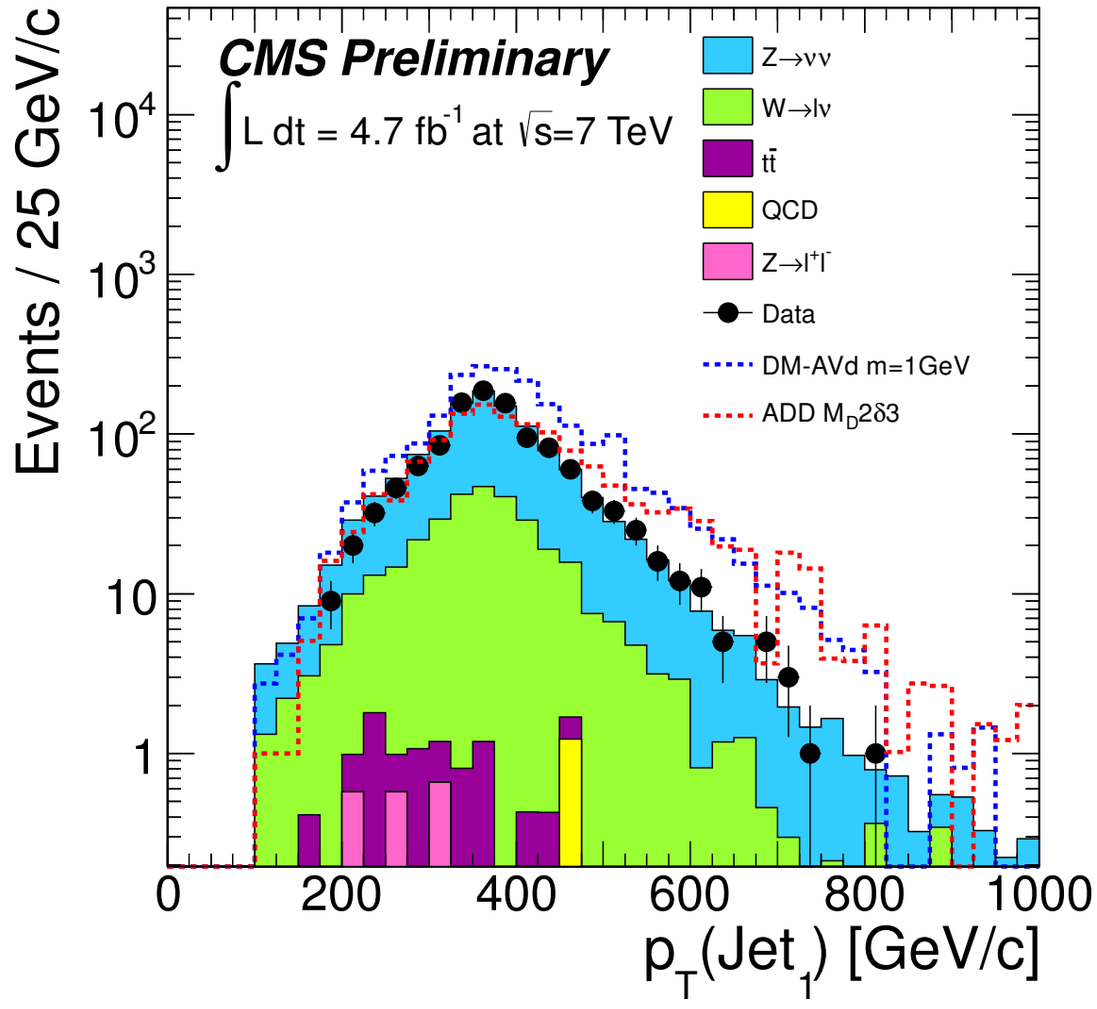
-veto events with isolated tracks





Results





this is what signal would look like , for axial vector interaction with DM mass = 1 GeV

Dominant backgrounds from Z-->vv (70%) and W+jets (~30%) are estimated from data

Results

Background process	Events
$Z \to \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142

No excess of events over expected SM backgrounds

Selecting monophoton events

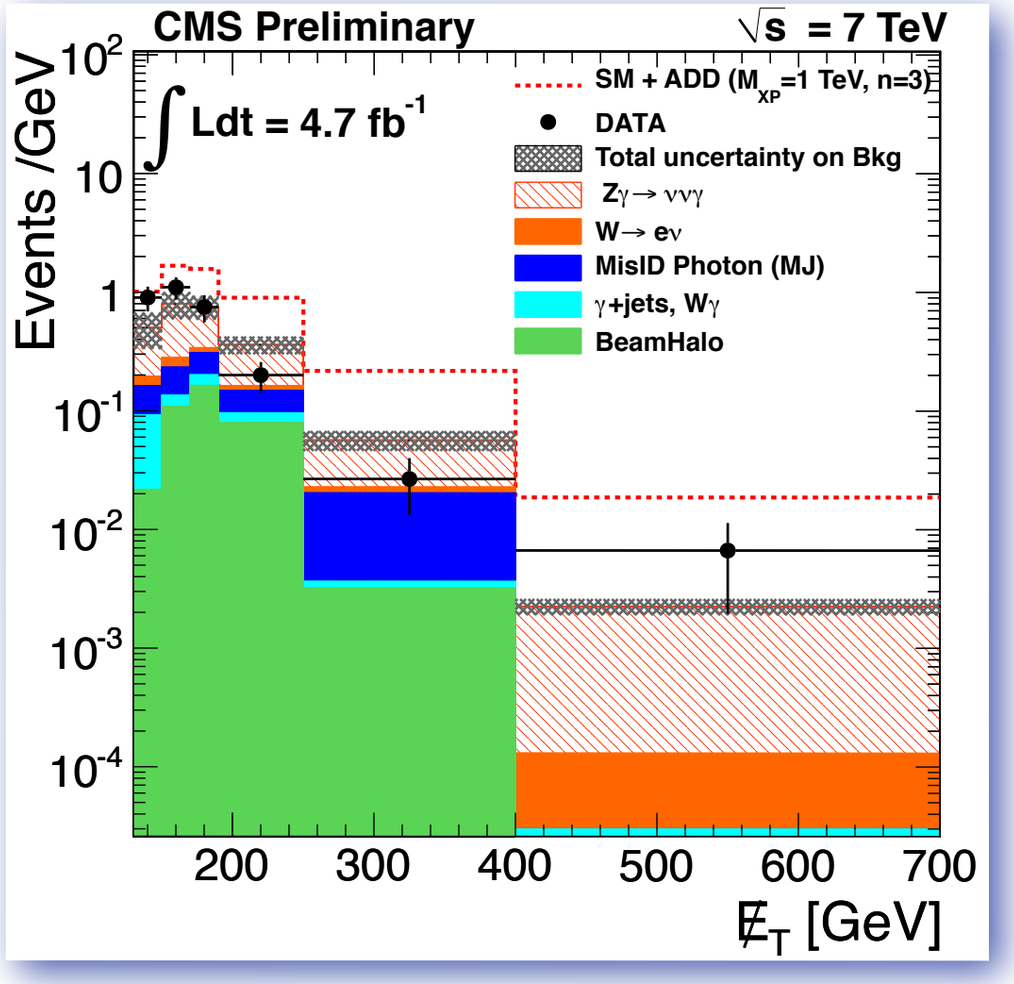
Photon selection

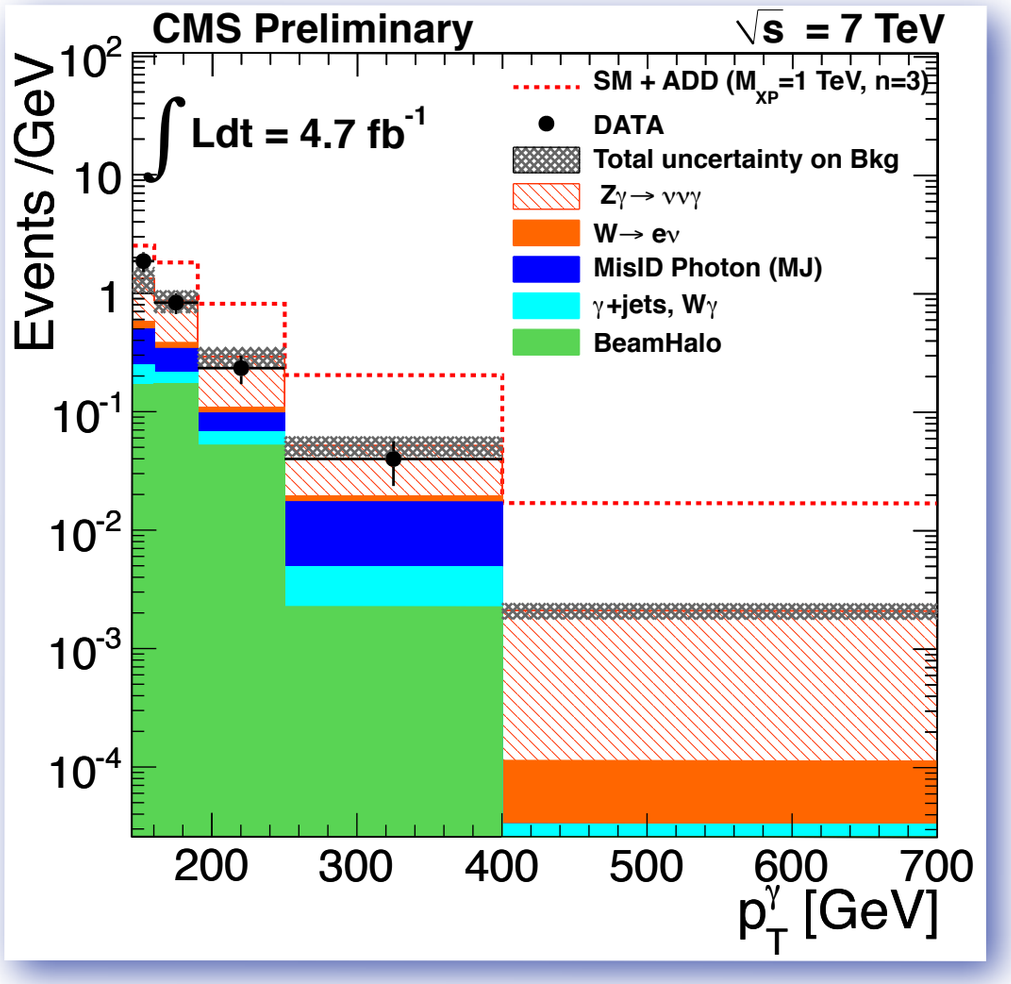
* p_T > 145 GeV
* Central region of detector, |η| < 1.4442
* Shower shape in calorimeter consistent with photon

MET

* MET > 130 GeV

Remove excessive hadronic activity





Results

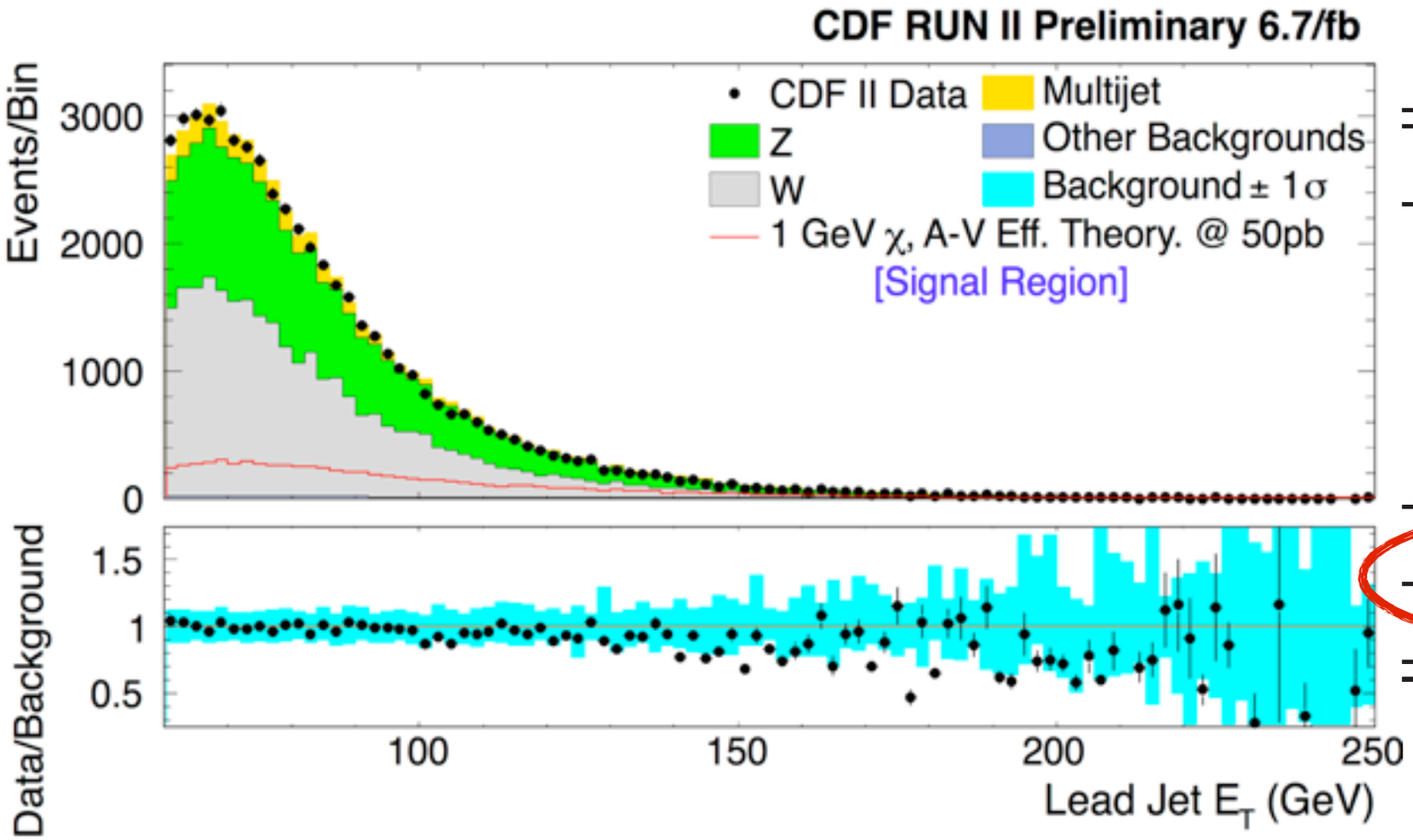
Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
Wγ	2.8 ± 0.9
γ+jet	0.5 ± 0.2
$\gamma\gamma$	0.5 ± 0.3
Z$(\nu\bar{\nu})\gamma$	42.4 ± 6.3
Total Background	71.9 ± 9.1
Total Observed Candidates	73

No excess of events over expected SM backgrounds

CDF monojet analysis

- MET > 60 GeV
- leading jet $p_T > 60$ GeV, $|\eta| < 1.1$
- $\Delta\phi$(MET,jet) requirements to reject QCD
- veto isolated tracks to reject EWK

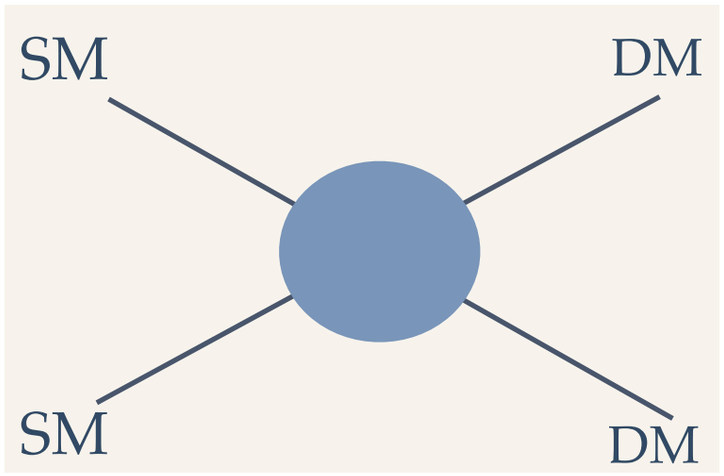
arXiv:1203.0742v1

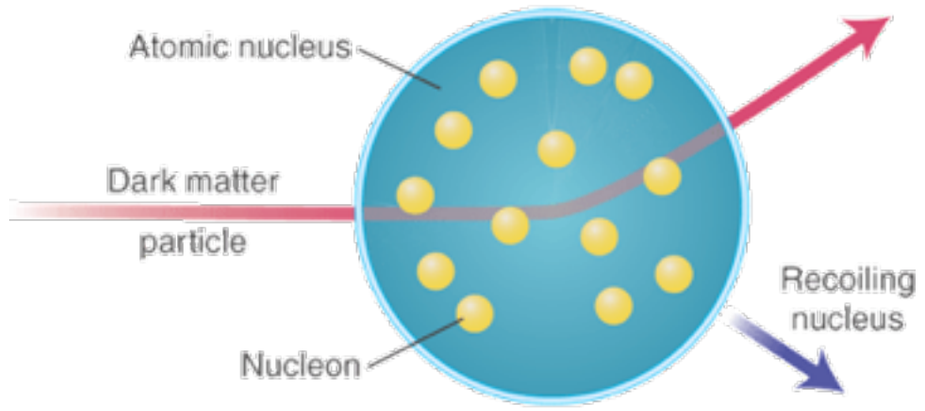


Source	Analysis
Z	22191 ± 2681
W	27892 ± 3735
Multijet	3278 ± 1639
Other	545 ± 39.3
Total model	53906 ± 6022
Data	52633

Setting limits on DM-nucleon cross section

Translating collider limits to the same plane as direct detection experiments





Vector operator

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O}^N = f_q^N \frac{\left(\bar{N}\gamma^\mu N\right)\left(\bar{\chi}\gamma_\mu\chi\right)}{\Lambda^2}$$

coefficient relates nucleon and quark operator

need to know quark content of nucleon

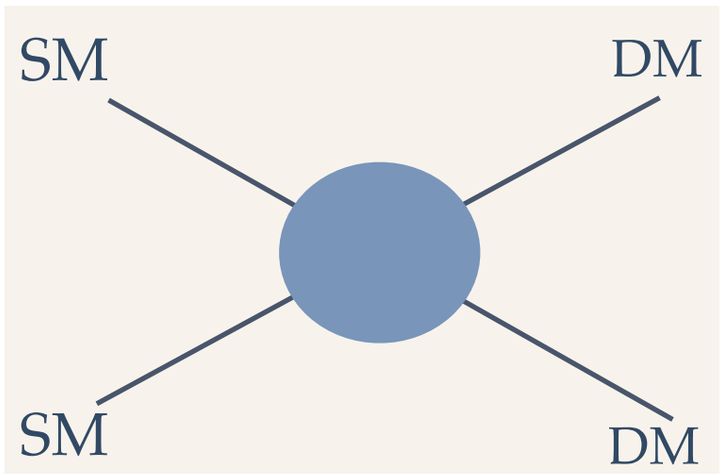
$$\sigma_{SI} = \frac{\mu^2}{\pi\Lambda^4} f_q^{N2}$$

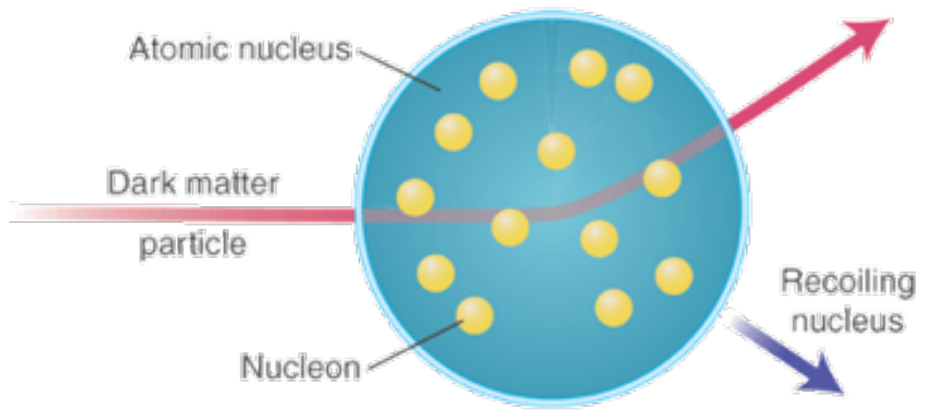
$$\text{where } \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

reduced mass of the DM-nucleon system

Setting limits on DM-nucleon cross section

Translating collider limits to the same plane as direct detection experiments





Vector operator

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$$\mathcal{O}^N = f_q^N \frac{\left(\bar{N}\gamma^\mu N\right)\left(\bar{\chi}\gamma_\mu\chi\right)}{\Lambda^2}$$

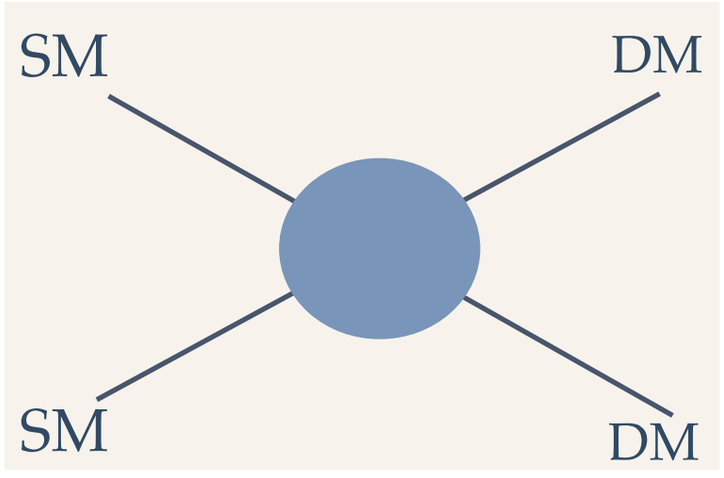
Upper limits on monojet/ monophoton cross sections converted to lower limits on Λ

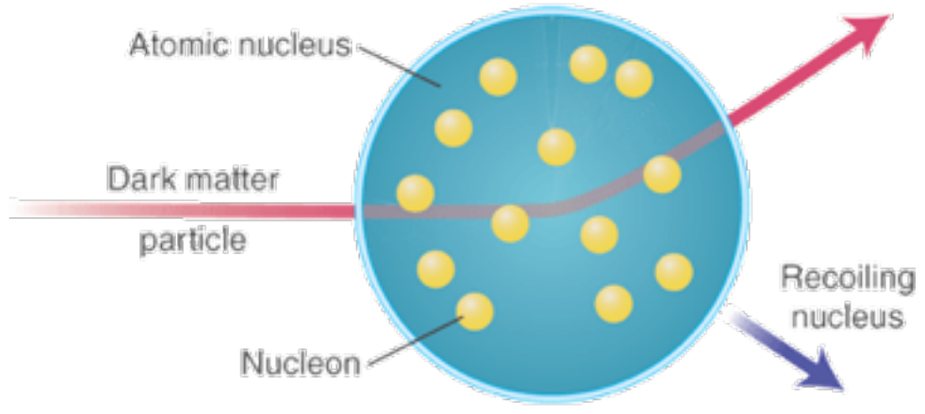
$$\sigma_{SI} = \frac{\mu^2}{\pi\Lambda^4} f_q^{N2}$$

Lower limits on Λ then translated to spin-independent DM-nucleon cross-section

Setting limits on DM-nucleon cross section

Translating collider limits to the same plane as direct detection experiments





Axial-vector operator

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

$$\mathcal{O}^{Nq} = \Delta_q^N \frac{(N\gamma^\mu\gamma_5 N)\,(\bar{\chi}\gamma_\mu\gamma_5\chi)}{\Lambda^2},$$

$$\sigma^{Nq} = \frac{3\,\mu^2}{\pi\,\Lambda^4}\,(\Delta_q^N)^2\,.$$

sum of quark helicities

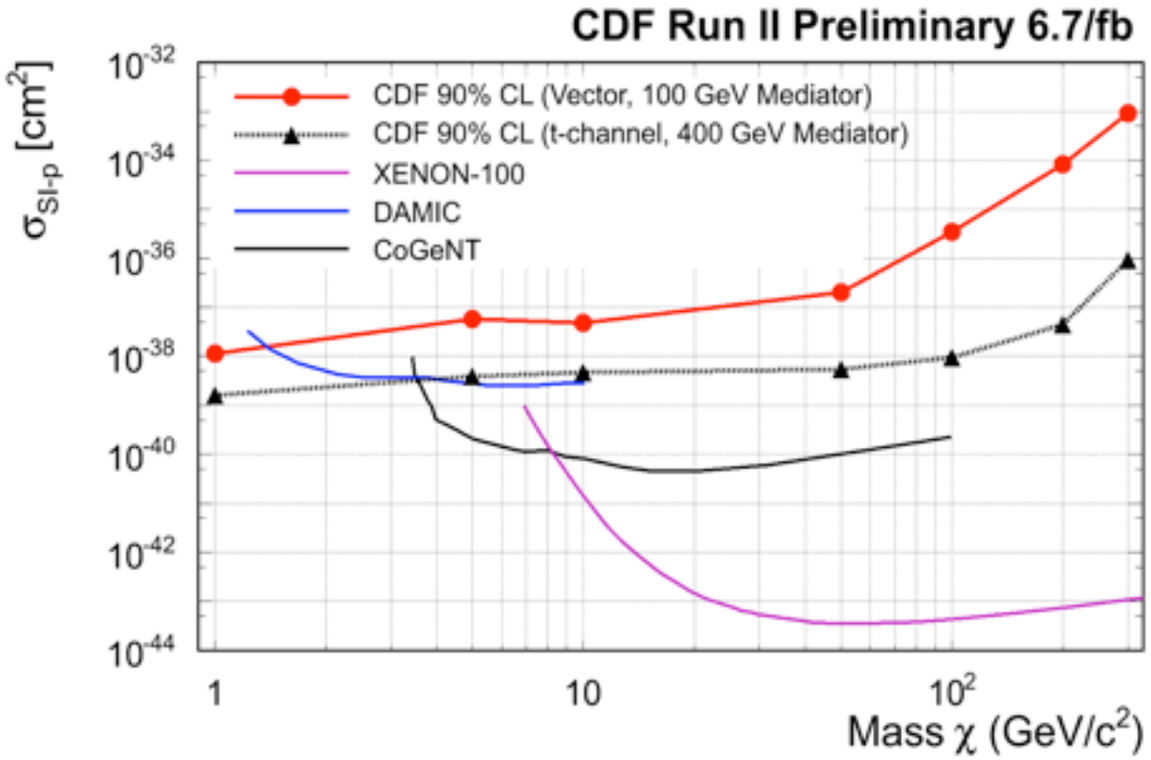
- Upper limits on monojet/monophoton cross sections converted to lower limits on Λ
- Lower limits on Λ then translated to spin-dependent DM-nucleon cross-section

Dark matter interpretation - CDF results

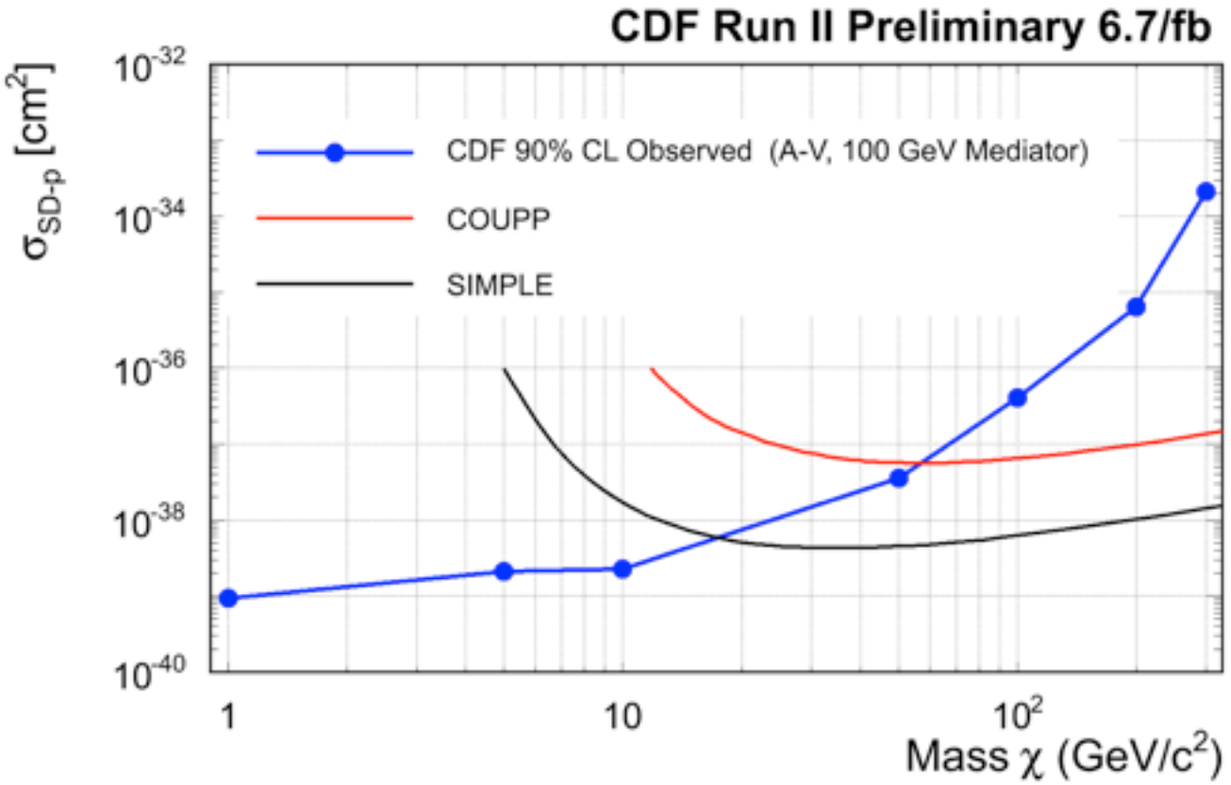
Light mediator case

- mediator mass = 100 GeV, 400 GeV

Spin-independent

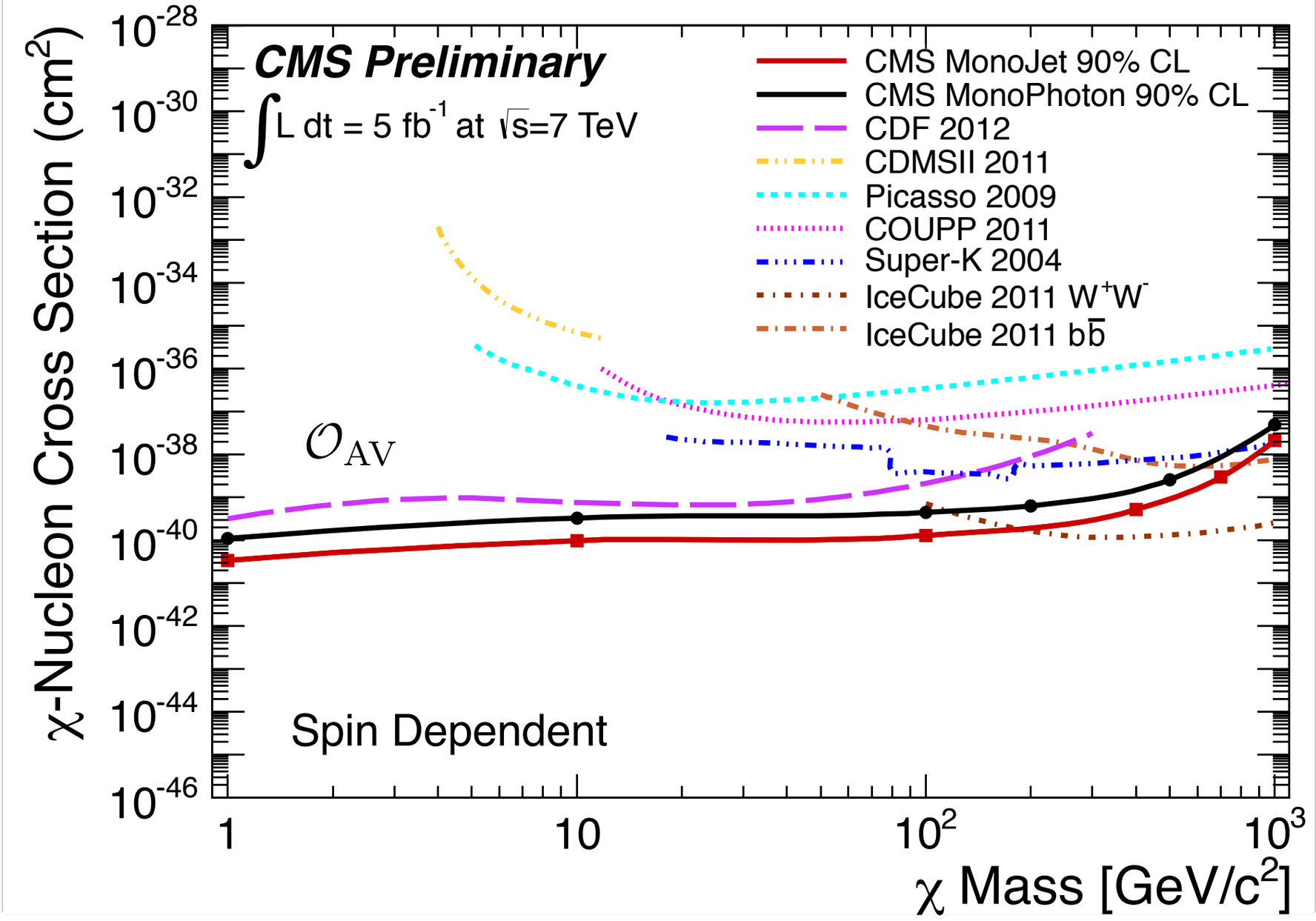


Spin-dependent



Dark matter spin dependent results

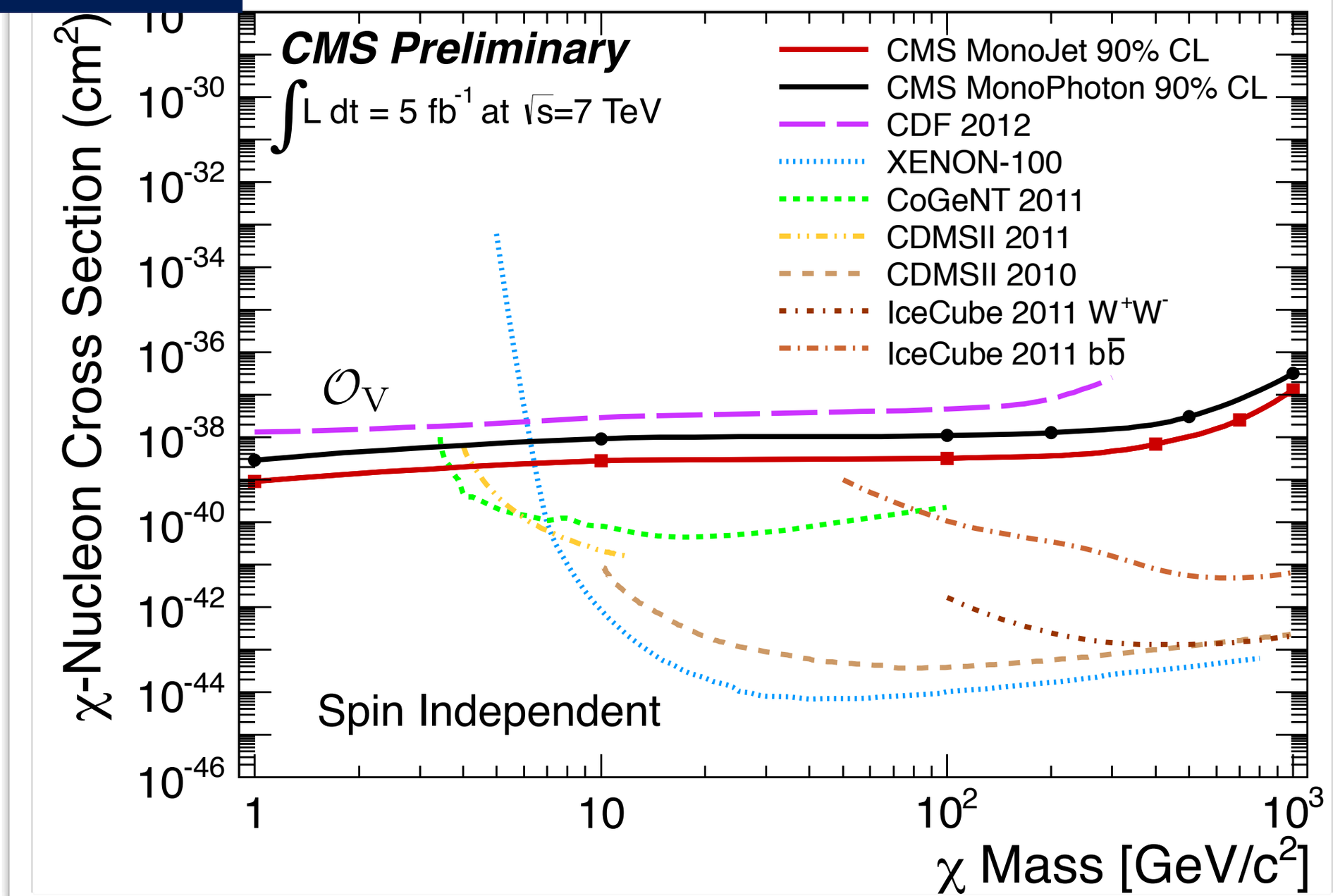
Contact interaction



Limits represent the most stringent constraints over almost entire 1 -1000 GeV mass range

Dark matter spin independent results

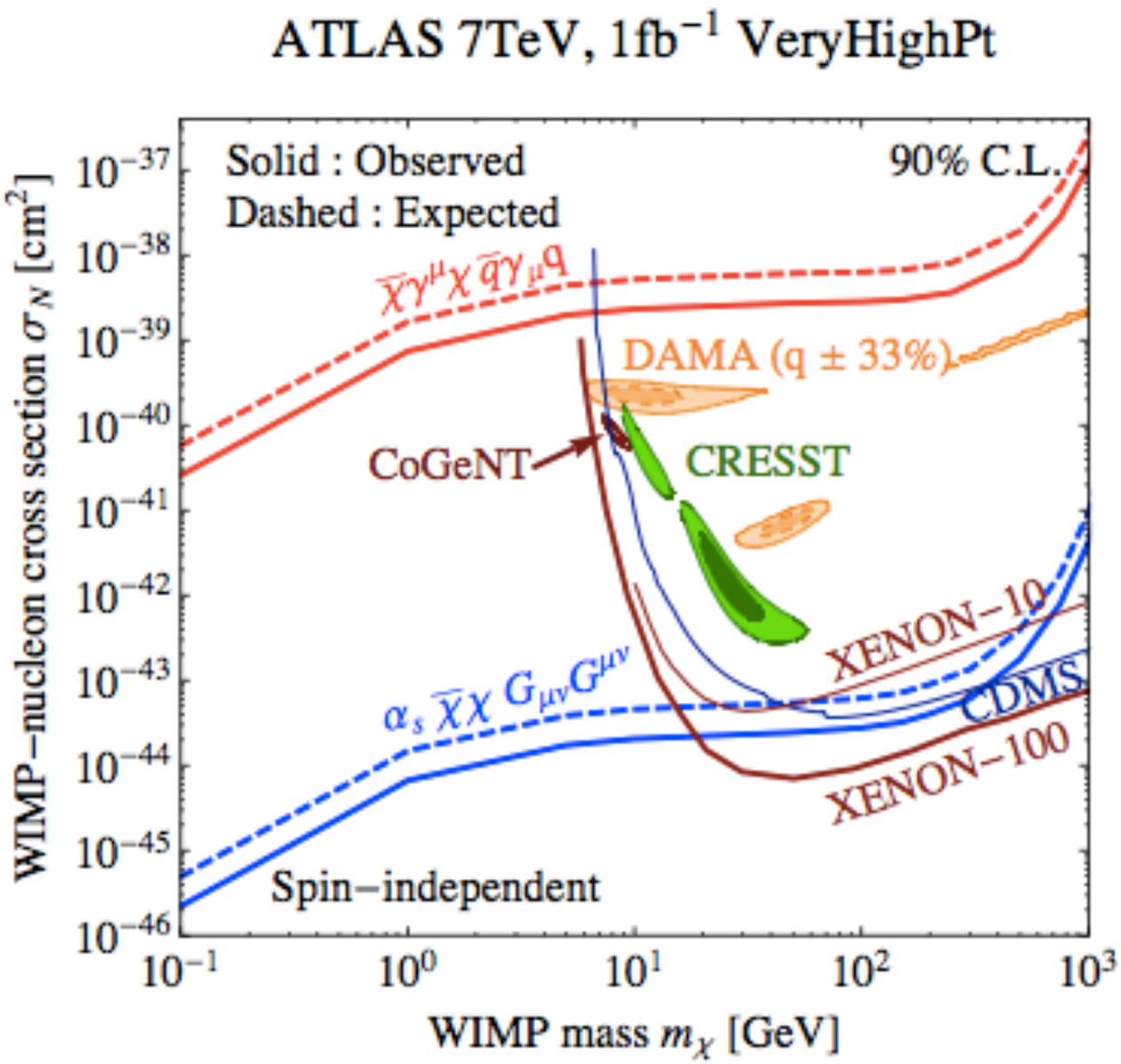
Contact interaction

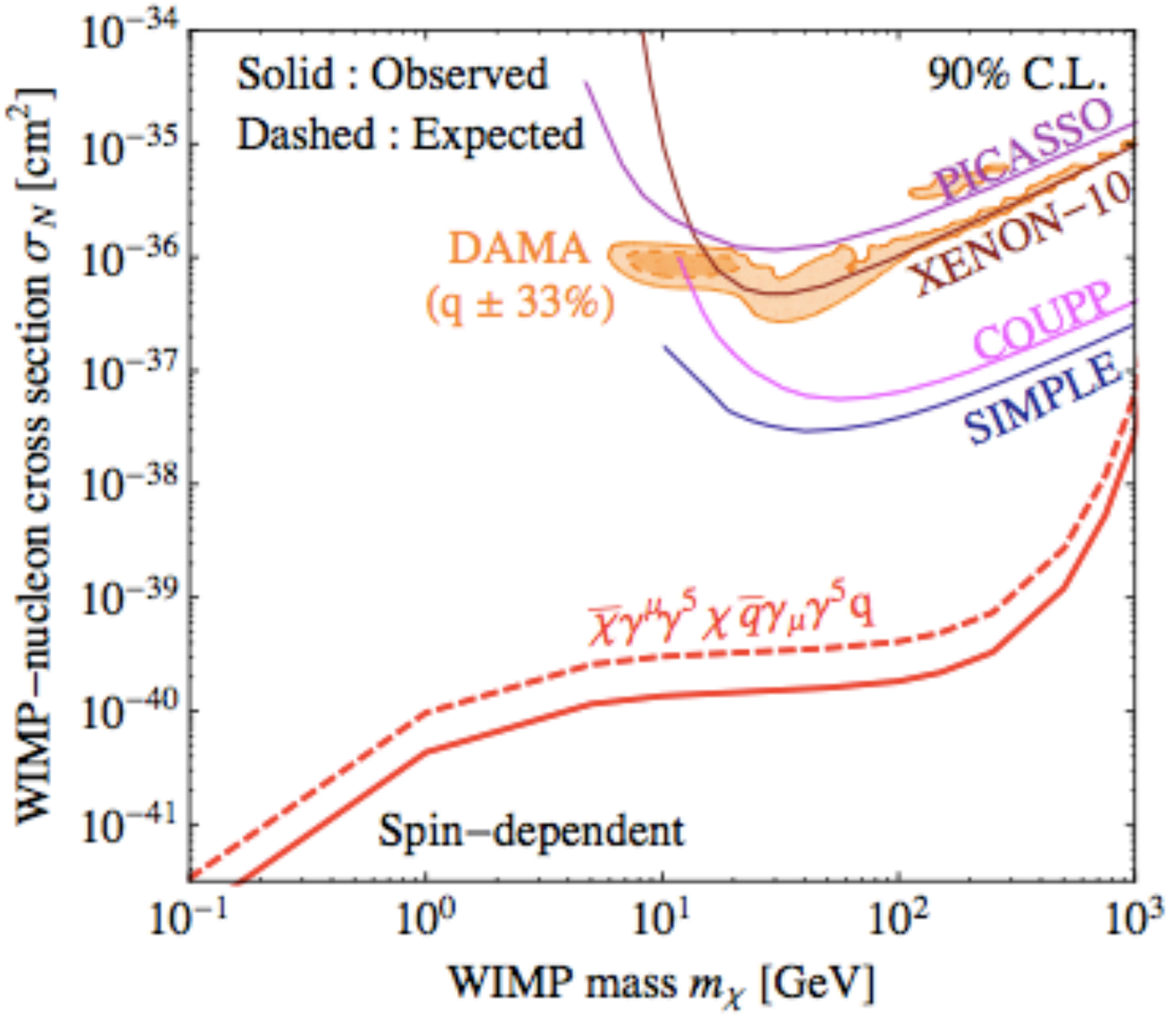


Best constraints for low mass dark matter, below 3.5 GeV, a region as yet unexplored by direct detection experiments

Interpretation of 1fb^{-1} ATLAS results

arXiv:1109.4398v1





ATLAS results coming soon.....

Summary

- Presented results from searches for dark matter at the Tevatron and LHC
- Searches in monojet and monophoton channels used to set limits on DM-nucleon cross-section
- Searches give competitive constraints for spin-dependent cross section over large DM mass range
- Extend the spin-independent region into low DM mass < 3.5 GeV, previously unexplored.
- Colliders constraints on DM complementary to those from direct detection and indirect detection